CLARREO as "NIST-in Orbit"

Bruce Wielicki
Dave Doelling
Don Garber
Dave Mac Donnell
Kory Priestley
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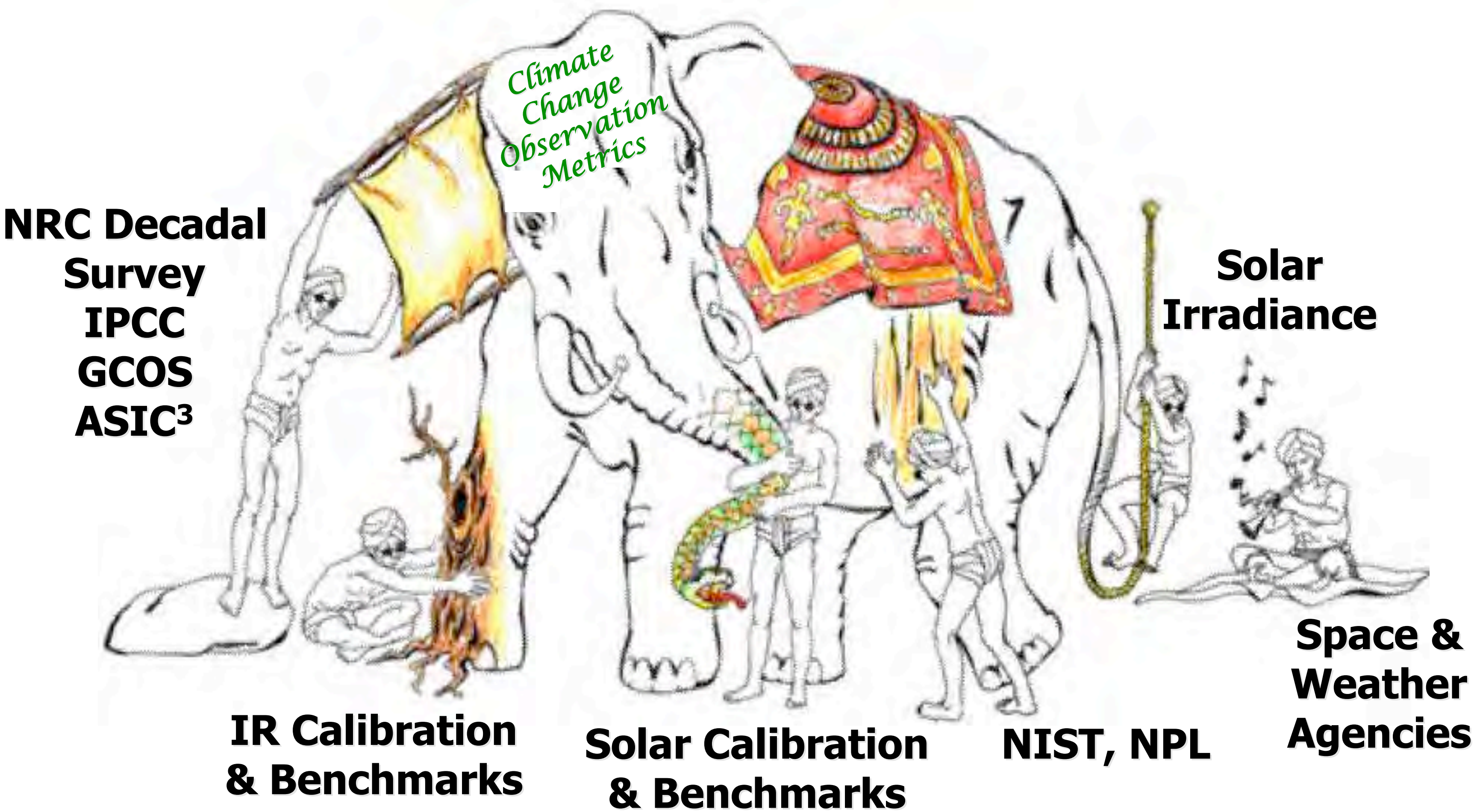
and input from many others…

NASA Langley Research Center

CLARREO Workshop
July 17-19, 2007

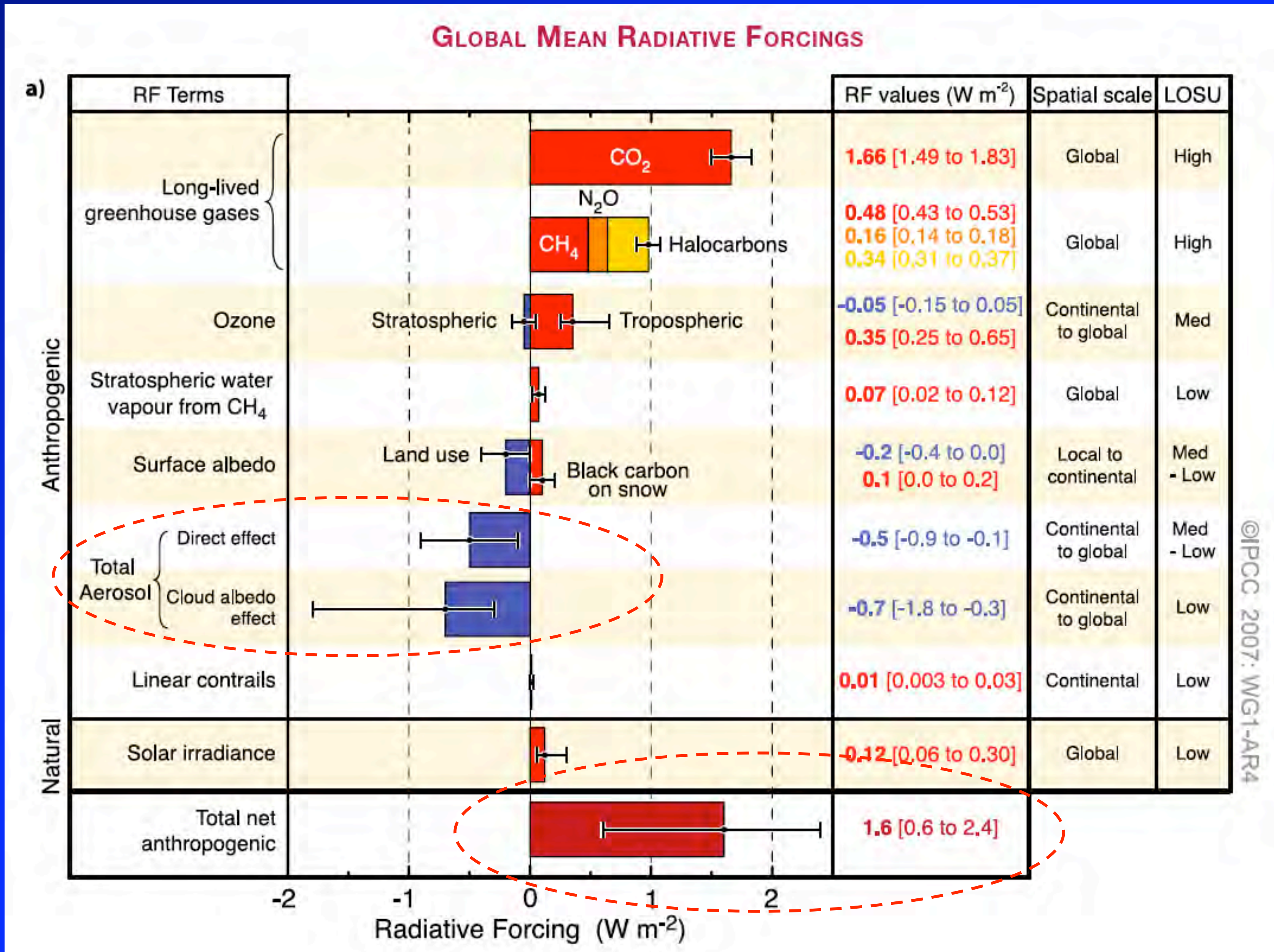
CLARREO and Climate Change

Groping Toward "The Truth, The Whole Truth, and Nothing But The Truth"

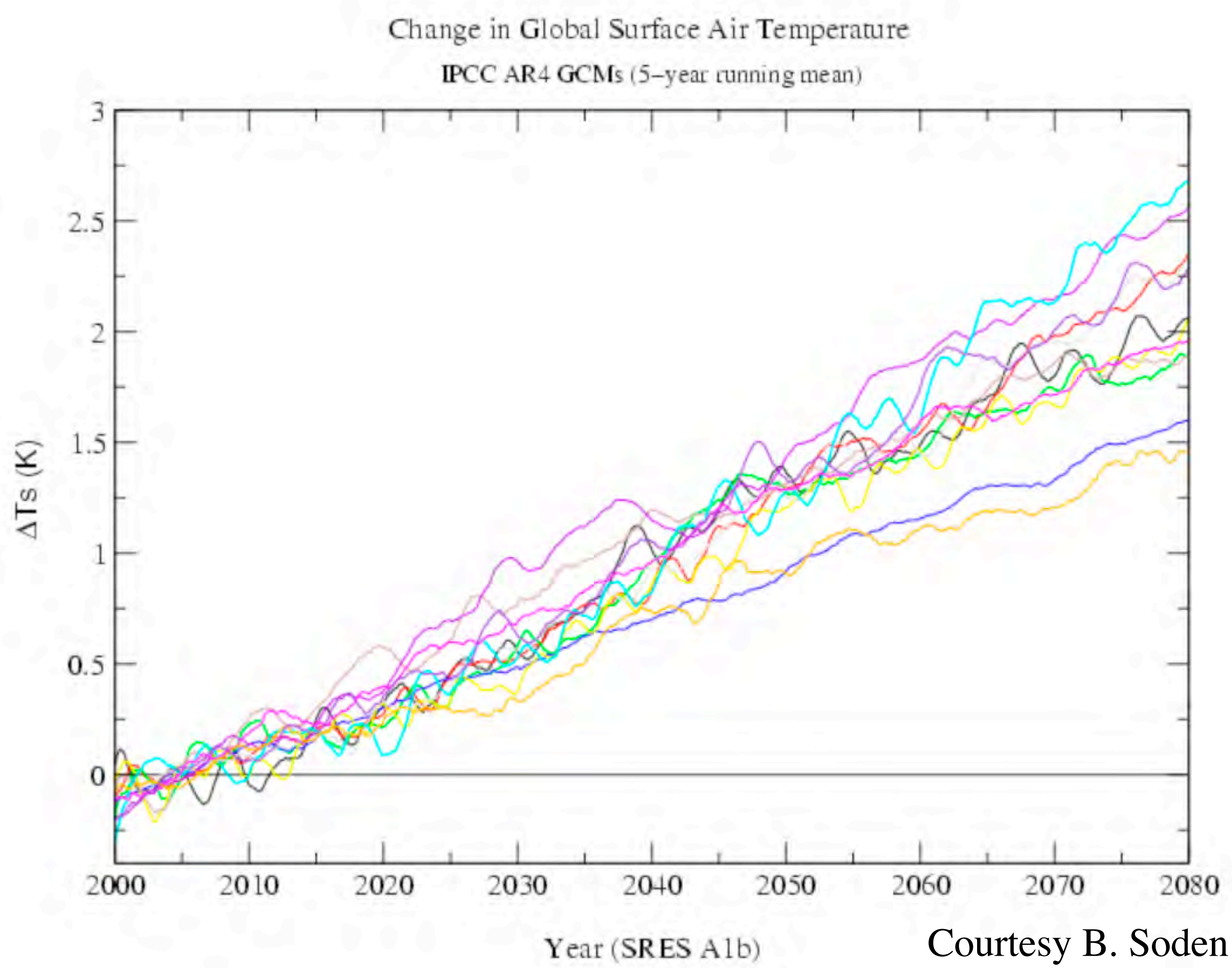


And the first blind man said, "To learn the truth, we must put all the parts together"

IPCC AR4 Radiative Forcing Chart



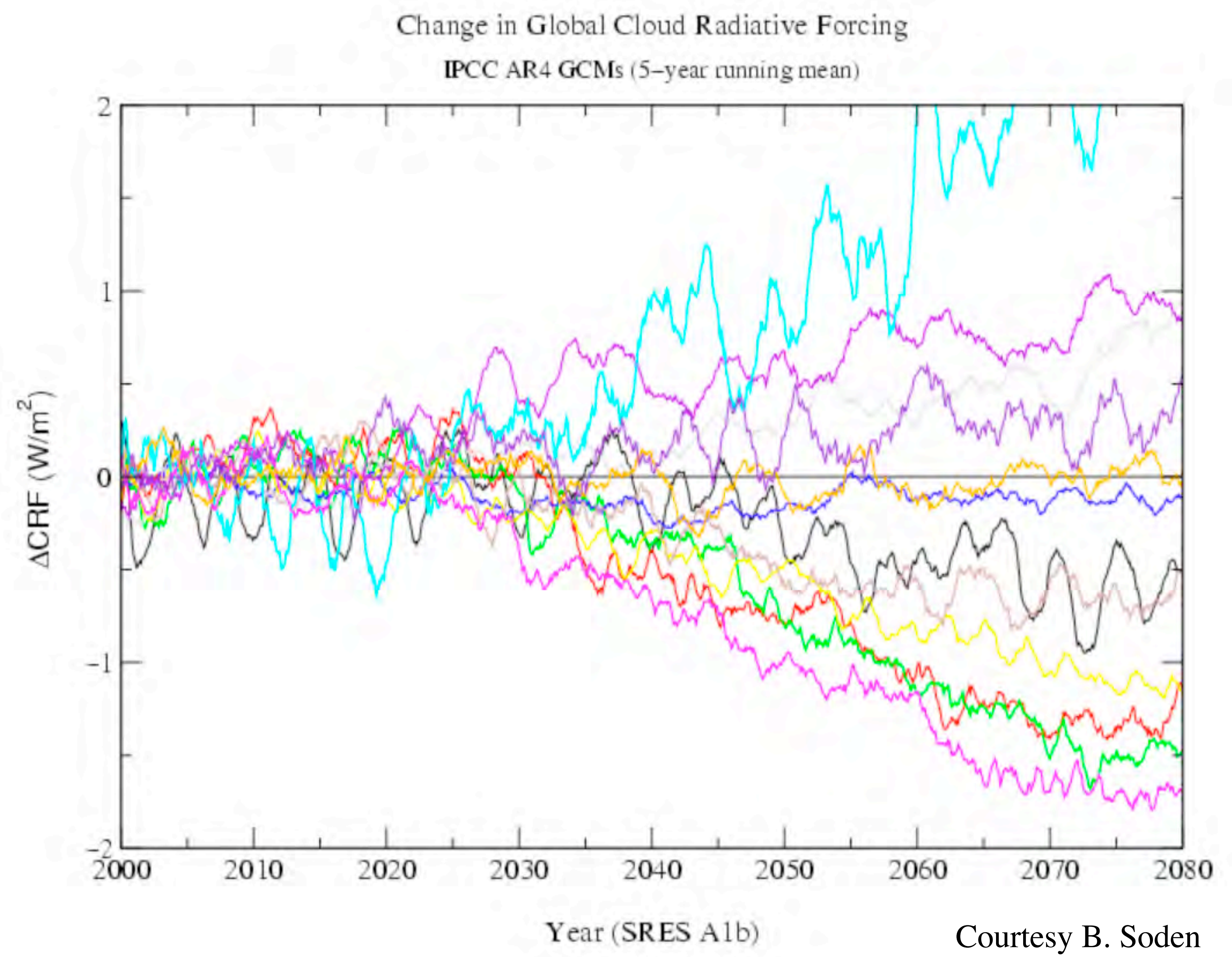
Why? IPCC Global Temperature Change



Courtesy B. Soden

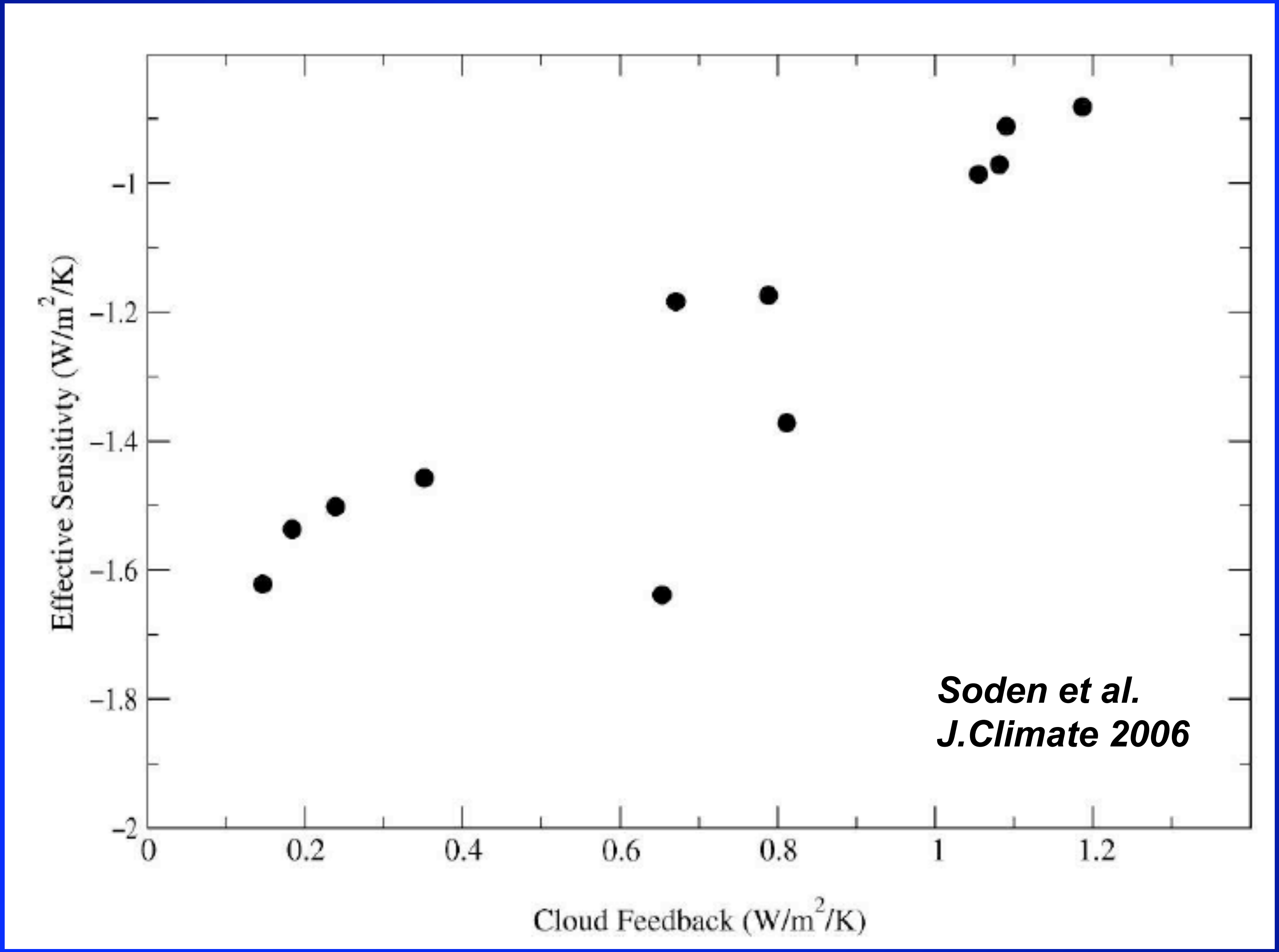
High sensitivity and low sensitivity climate models don't separate clearly in global temperature change until 2040: temperature trends along not enough.

Why? IPCC Cloud Radiative Forcing Change



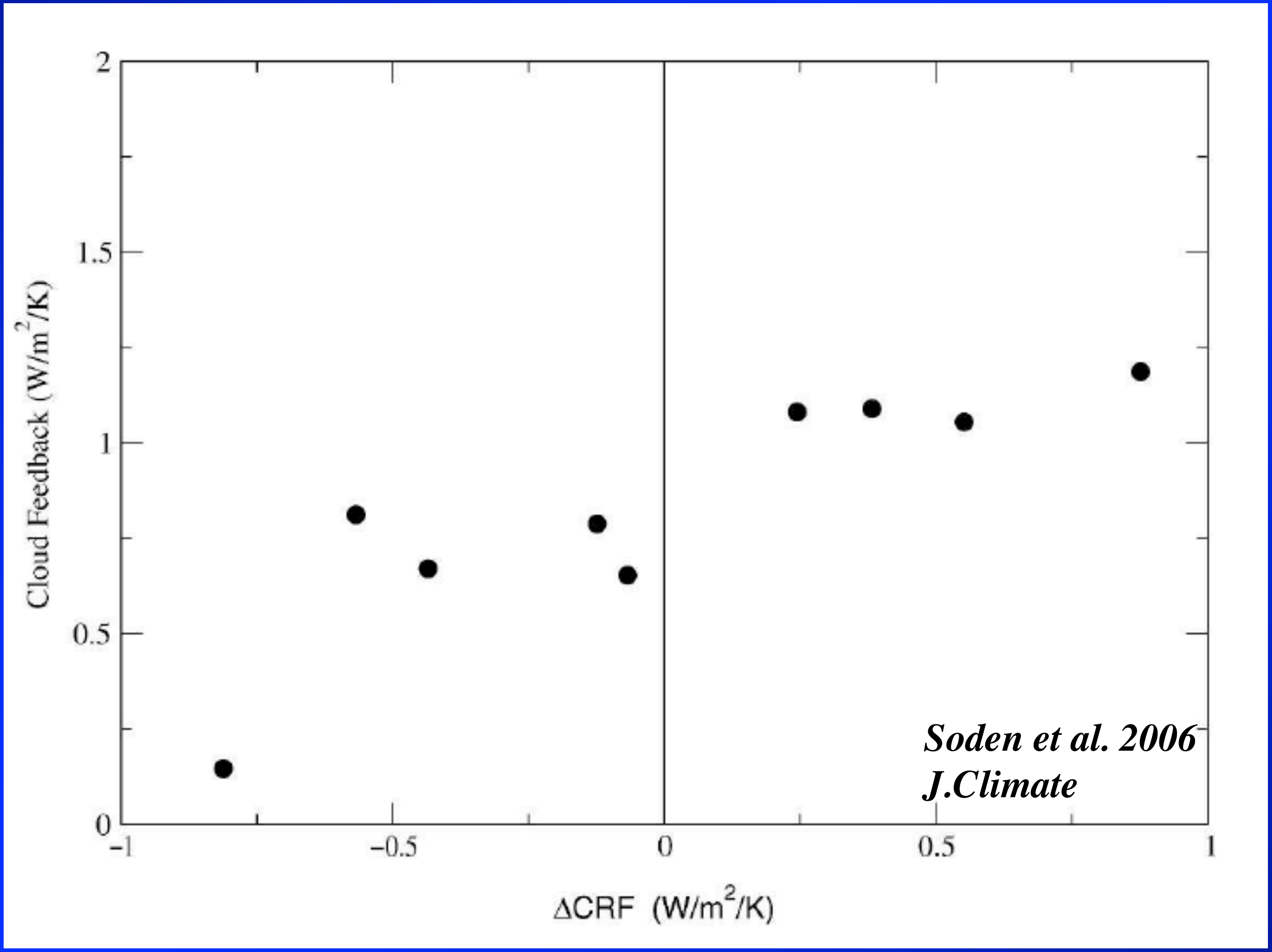
Courtesy B. Soden

Climate Sensitivity vs Cloud Feedback
IPCC AR4 Models



Climate sensitivity is essentially linear in cloud feedback

Cloud Feedback vs Cloud Radiative Forcing
IPCC AR4 Models



Cloud Feedback is essentially linear in cloud radiative forcing change

What are key climate sensitivity metrics?

IPCC AR4 Summary:

The possibility of developing model capability measures ('metrics'), based on the above evaluation methods, that can be used to narrow uncertainty by providing quantitative constraints on model climate projections, has been explored for the first time using model ensembles. While these methods show promise, a proven set of measures has yet to be established

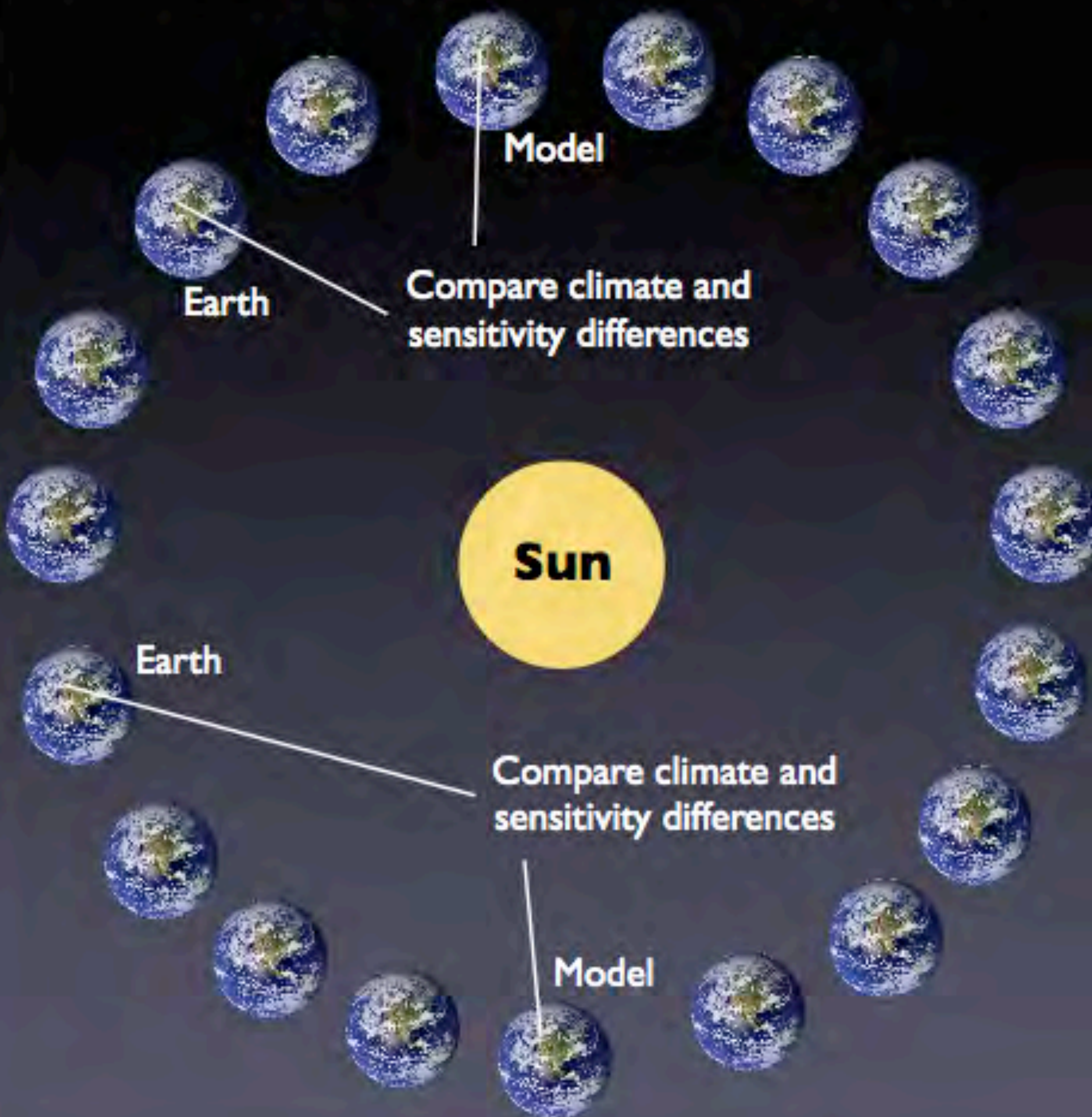
What can we do?

Perturbed Physics Ensembles

Where next?

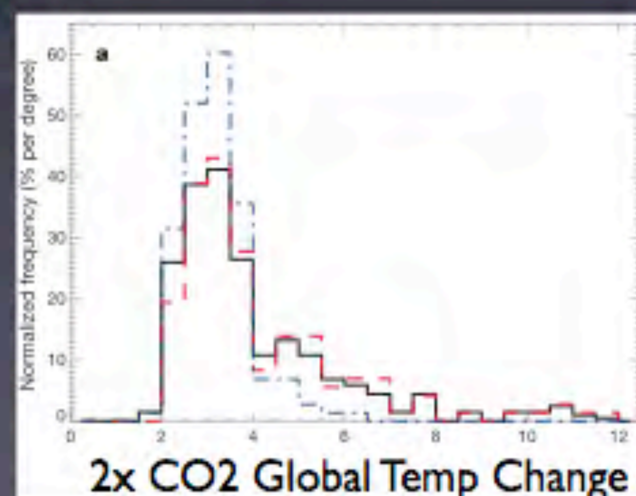
Coupled ocean atmosphere model runs, more complete output metrics, realistic 20th to 21st century forcing runs

60,000 Earth-Like Planets

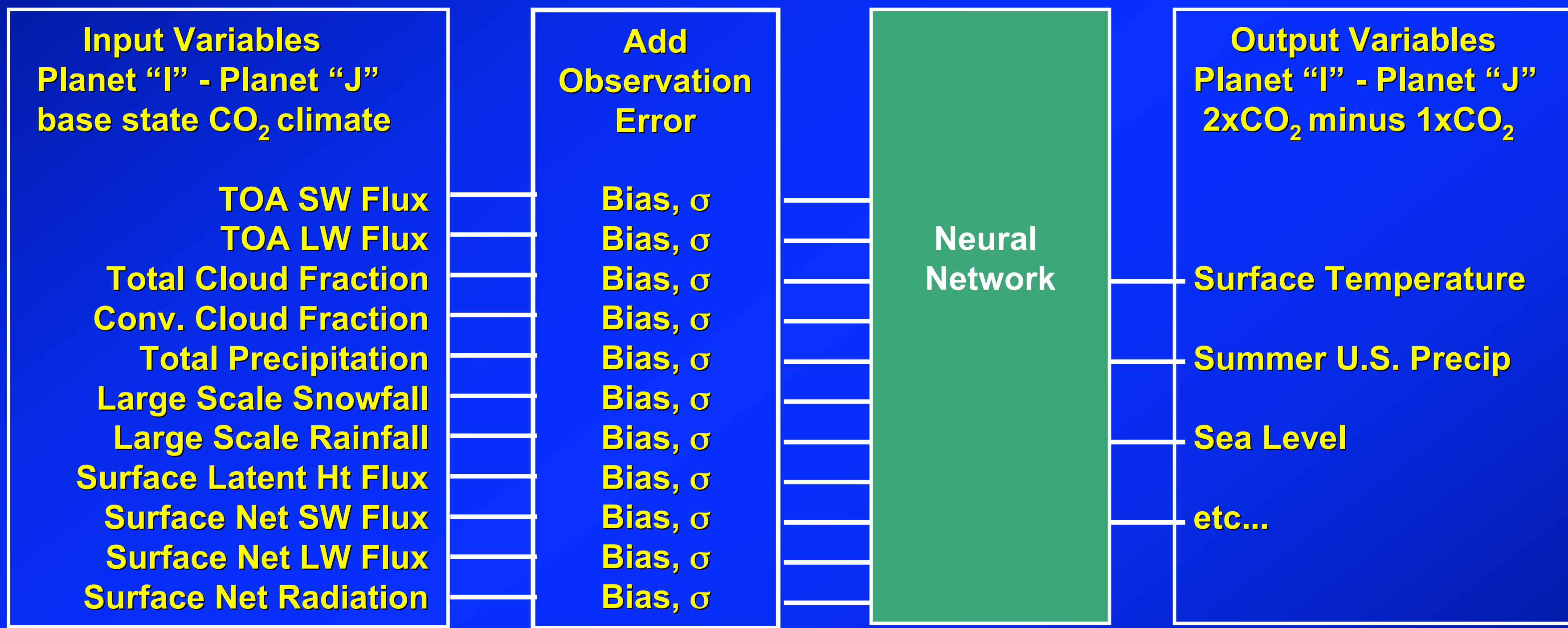


climateprediction.net:
constant known physics
vary uncertain physics
Run for normal CO_2
Run for doubled CO_2

Stainforth et al., 2005, Nature



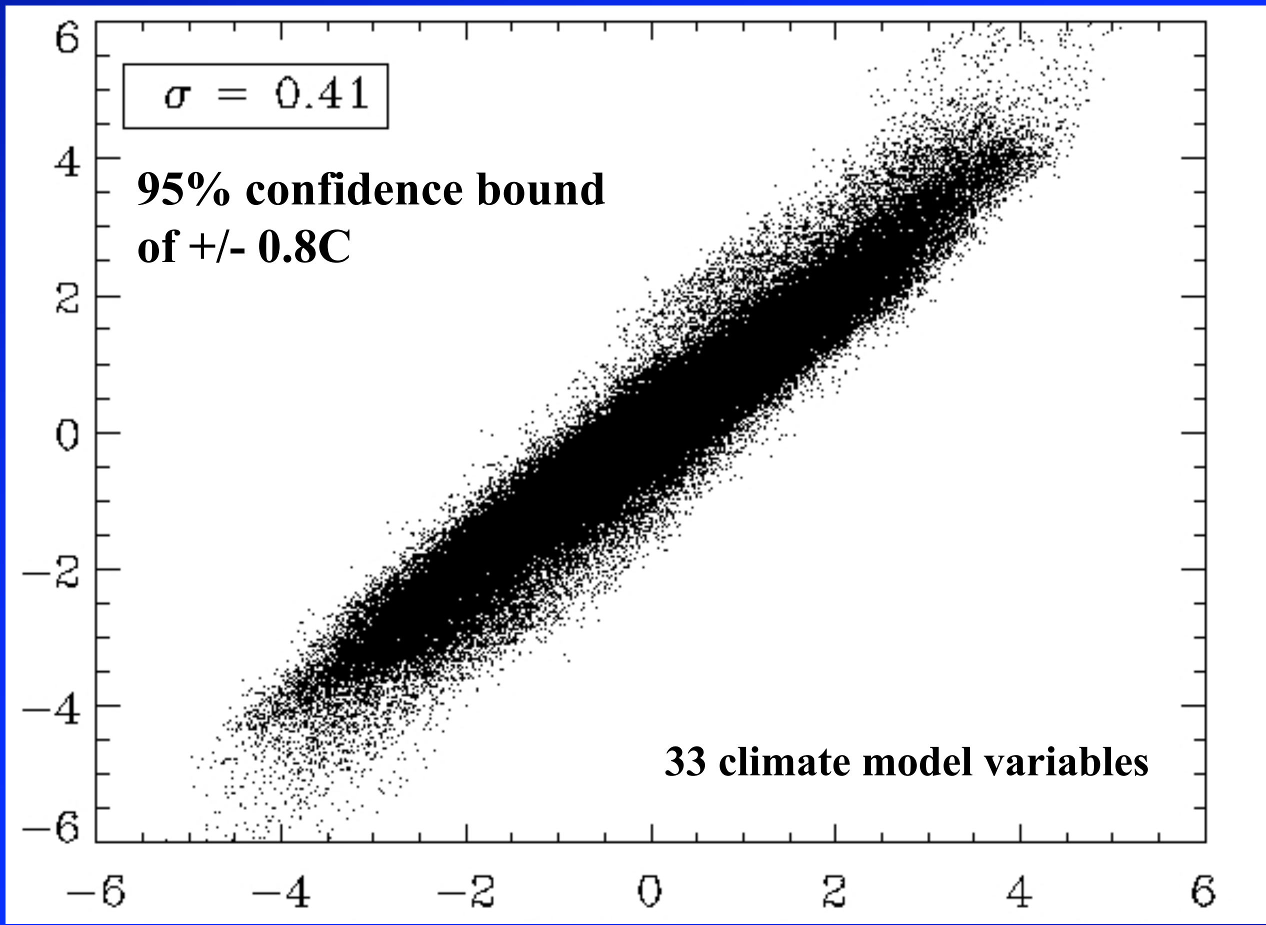
Neural Net Structure
Climate OSSEs



Difference in neural net performance with and without observation errors
Isolates effect of observation error on constraining climate uncertainty

Neural Net Prediction of Climate Sensitivity

Planet "I" minus Planet "J"
Doubled CO_2 Global Temp Change



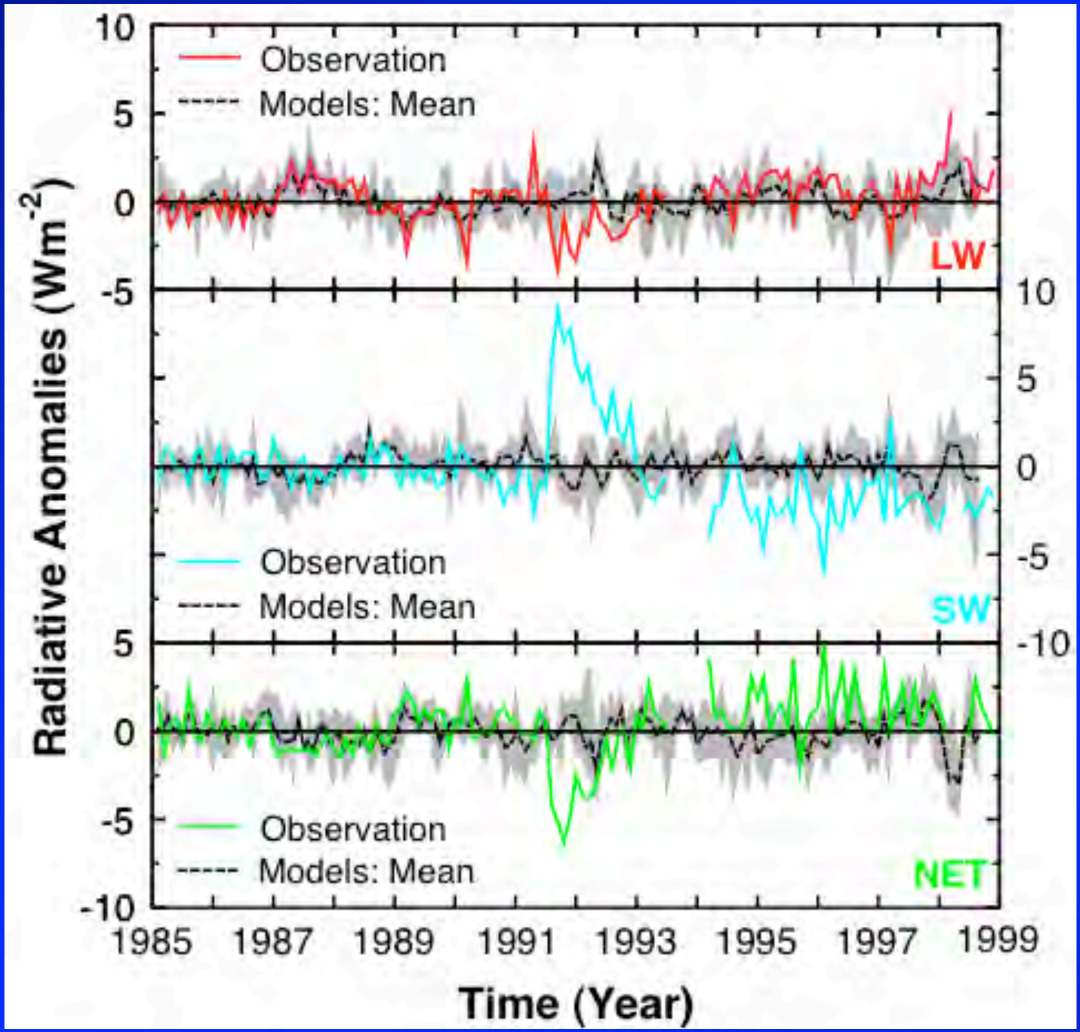
Neural Net Prediction: Doubled CO_2 Global Temp Change
(uses Planet I and J normal CO_2 climate only)

Y. Hu, B. Wielicki, M. Allen

Early Conclusions Using 2500 Mixed Layer Models Doubled CO_2 Climate Sensitivity

- Climate change metrics (e.g. decadal change) are much more powerful constraints than base state (e.g. global maps)
- Neural net 2.5 times more accurate than linear regression for base state metrics: these are very nonlinear
- Cross model applicability (UKMO trained but test on IPCC) is not robust for base state metrics, but is robust for climate change metrics.
- At global scale, energetics variables are more powerful than dynamics
- At regional climate metrics will likely involve both energetics and dynamics
- Observation system error degrades ability to constrain climate sensitivity rapidly as errors exceed 25% of expected climate change

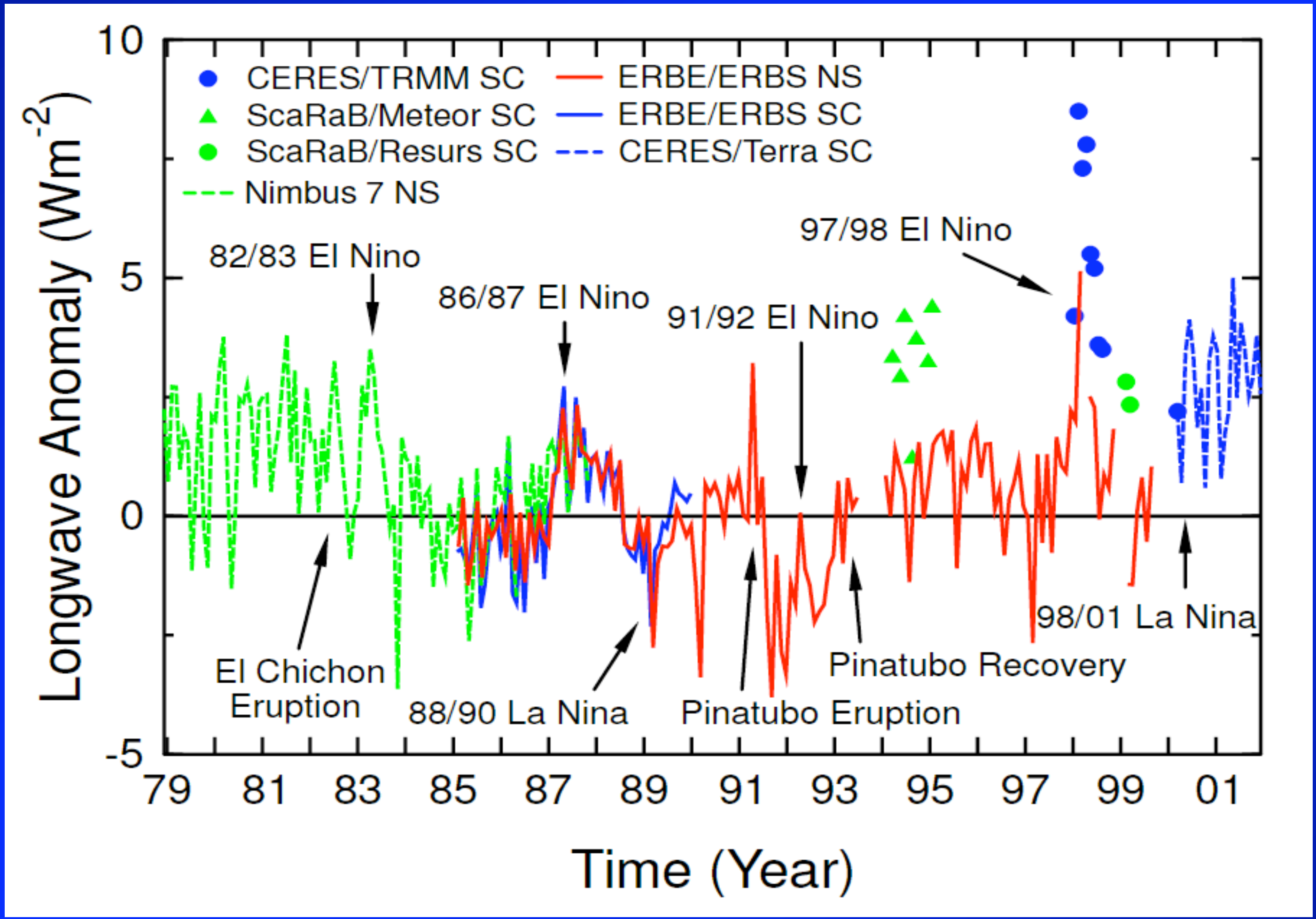
Tropical (20S - 20N) TOA Radiation Anomalies: Observations vs. Climate Models



- Model "noise" 0.3 Wm^{-2}
- Climate Signals ~ 2 Wm^{-2}
- Net tropical heating in 90s
- Opposite sign of "Iris"
- Climate Forcing:
  0.6 Wm^{-2} / decade
- 25% Cloud Feedback:
  0.15 Wm^{-2} / decade
  0.5% of TOA LW CRF
  0.3% of TOA SW CRF
  0.8% of TOA Net CRF
- Reqmts: Ohring et al. (BAMS, Sept 2005)
- Figure from Wong et al. J.Climate, 2006

High Accuracy Multi-Decadal Records Critical: Variability vs Anthropogenic

Tropical (20S - 20N) TOA Radiation Anomalies: ERBE/ScaRaB/CERES Comparisons

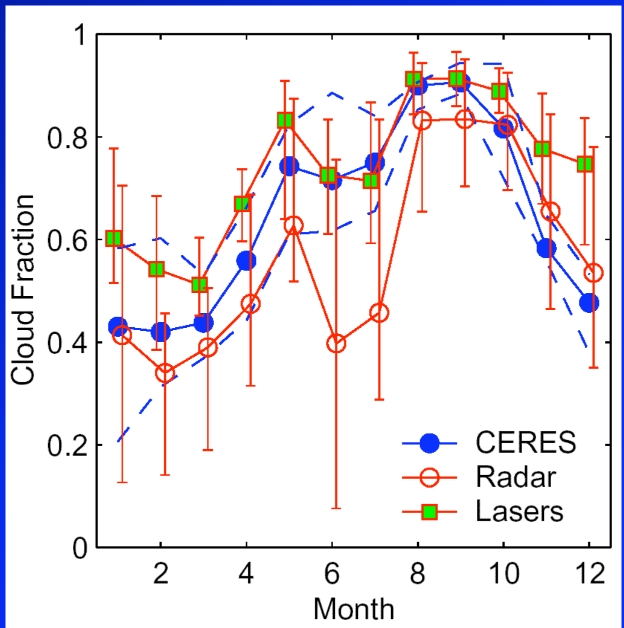


Best absolute accuracy of 0.5 to 2% insufficient for climate anomalies
Overlap is Critical: stability capability exceeds absolute accuracy

Wong et al., J. Climate, 2006

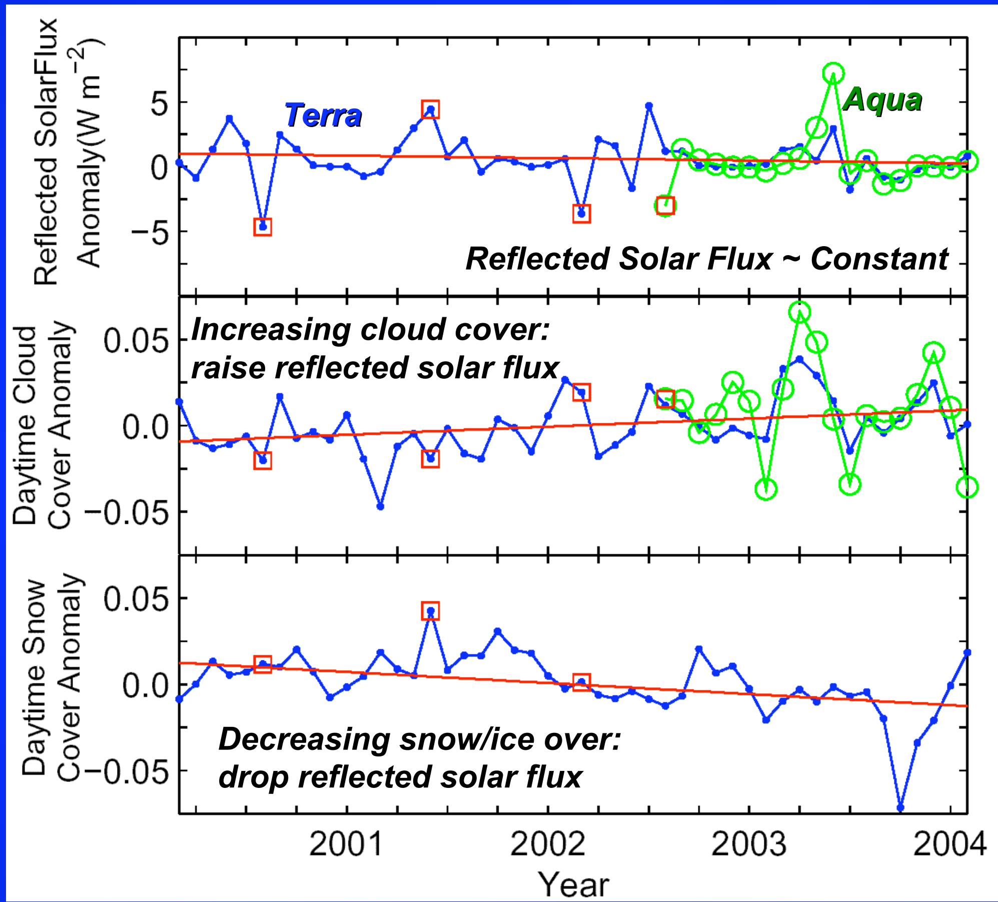
Arctic Warming: Are clouds offsetting much of the positive feedback of decreasing snow and ice?

Cloud Fraction at Barrow Alaska



CERES cloud analysis using MODIS data shows new polar cloud data compares well with surface lidar & radar from the DOE ARM site

Arctic (60N-90N) Trends from Terra & Aqua



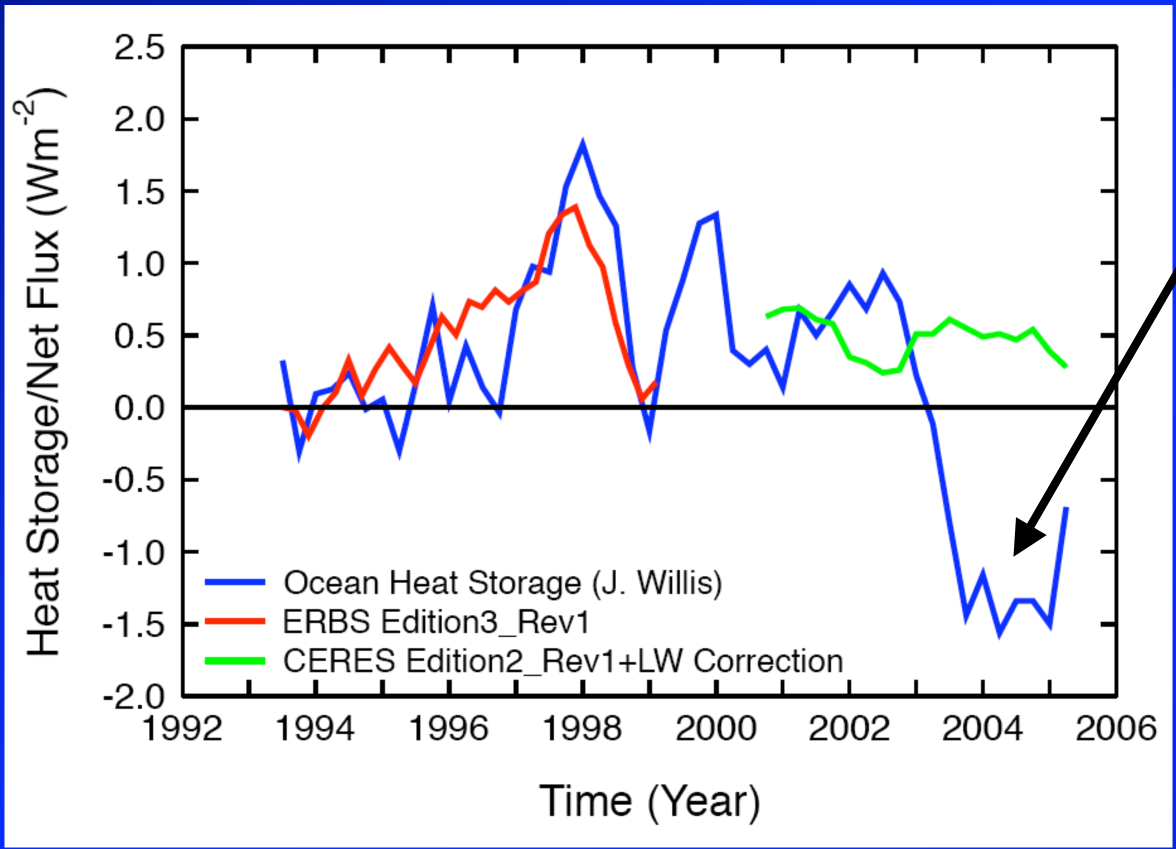
Currently, increasing Polar cloudiness is offsetting most of the positive climate feedback of decreasing Arctic snow and ice.

Will it continue?

Kato et al., GRL, 2006

Recent Ocean Cooling? No Global Warming?

A case study in the need for independent observations & analysis



Recent Ocean Cooling?
Lyman et al., Science 2006

Net Radiation(CERES): No

Altimeter Sea Level: No

GRACE Ice Sheet: No

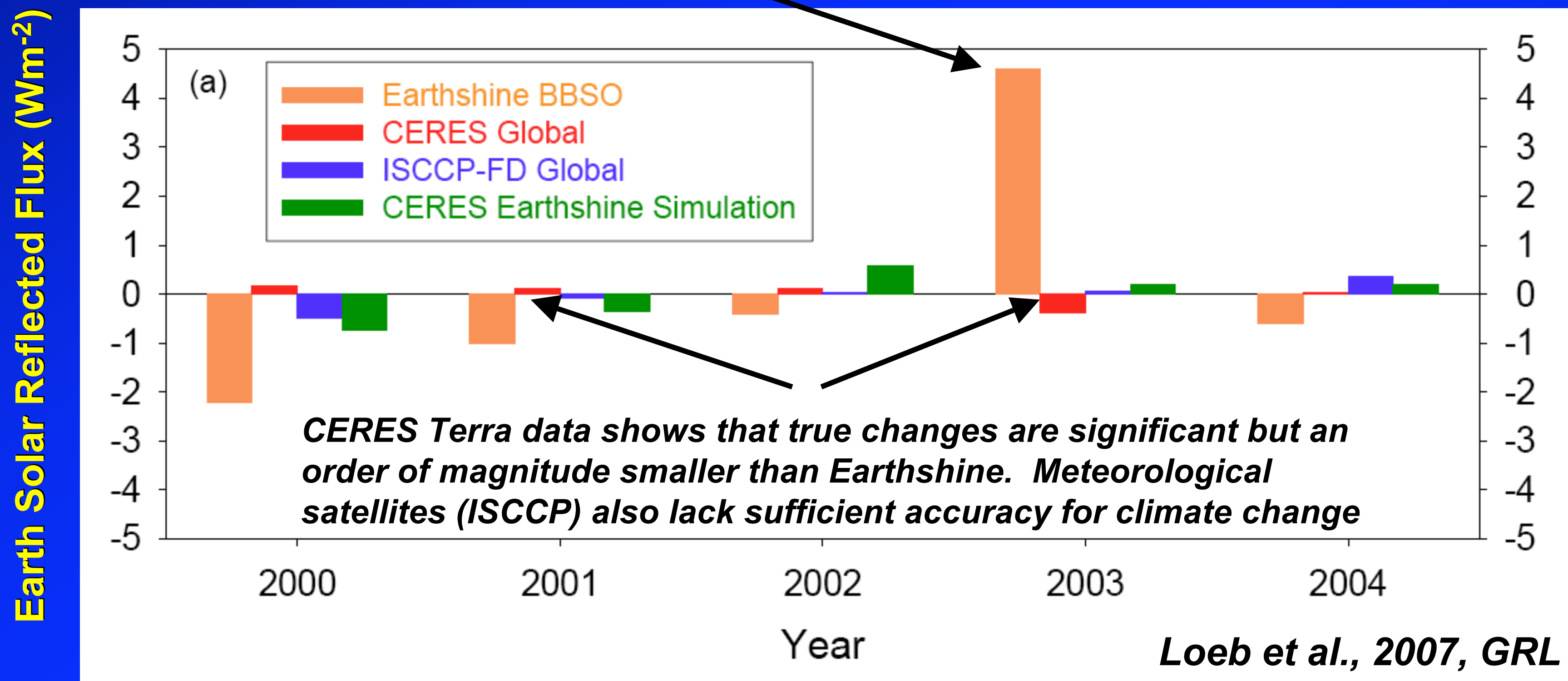
1992 to 2003 data from Wong et al. J. Climate 2006

The answer: warm bias in XBT in-situ data (dominate pre-2002) cold bias in ARGO in-situ data (dominate post 2002): cooling in 2004/5 vanishes when bias is corrected. mystery solved. Paper on in-situ biases submitted to GRL (Willis et al.)

Ocean Warming in 2003-2005 similar to average warming over 1993-2003. Remains consistent with ocean heating predicted by IPCC climate models

Earthshine: Climate Fact or Fantasy?

Earthshine data implies large change of 6 Wm^{-2} in global reflected solar flux: 6% and 10 times the decadal anthropogenic radiative forcing of 0.6 W/m^2. Is the Earth's reflectance changing? (Palle et al., Science, 2004):

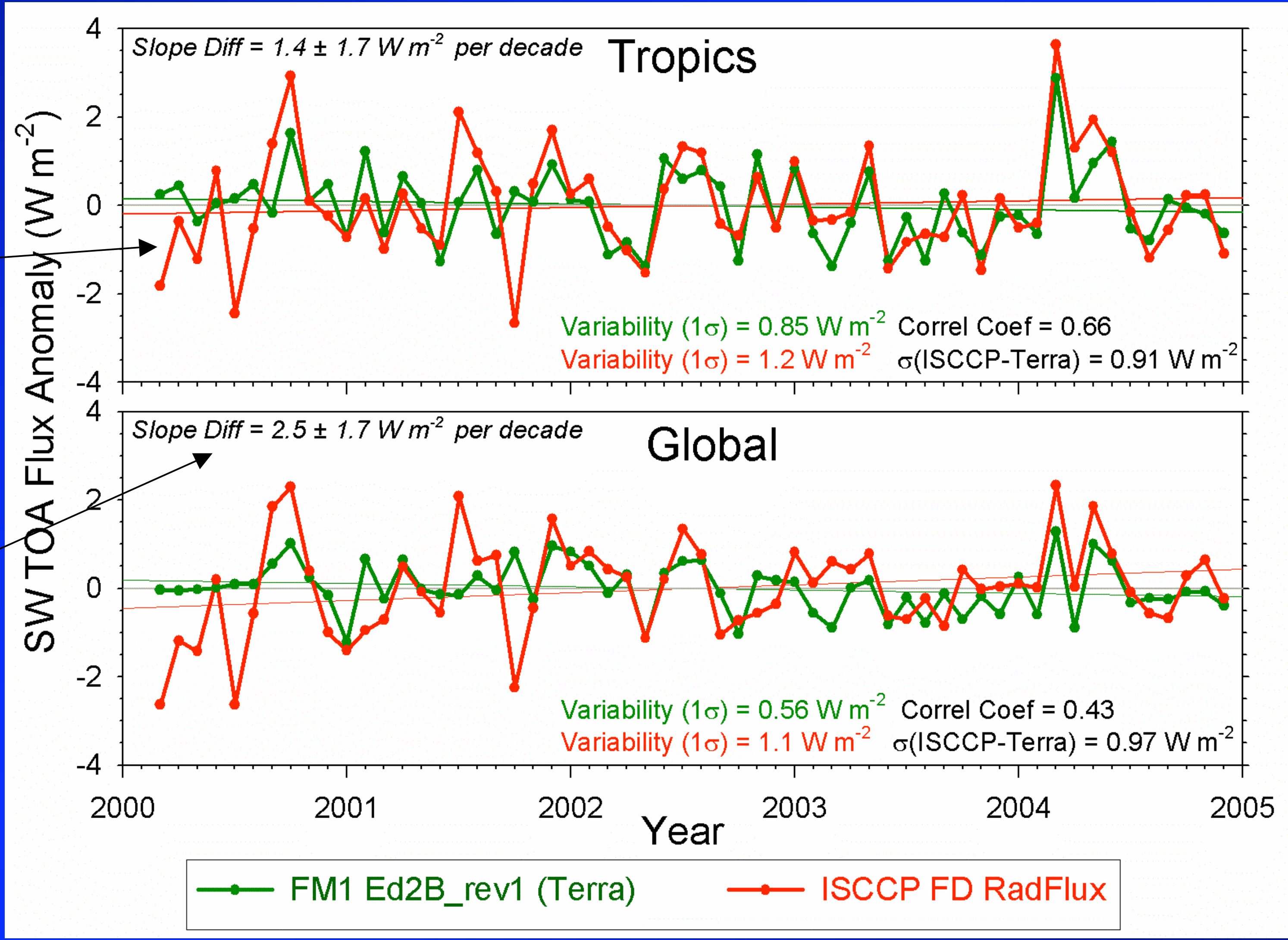


Conclusion: ***Earthshine data is neither accurate enough nor sampled well enough to reach climate accuracy as a global reflectance measurement. Erroneous results led to large and unnecessary confusion in the public & climate change community. The CERES results showing the correct result were used in recent IPCC AR4 report.***

How well can we pull climate records from meteorological satellite data like ISCCP from geostationary?

Geo calibration & sampling errors dominate inter-annual signals

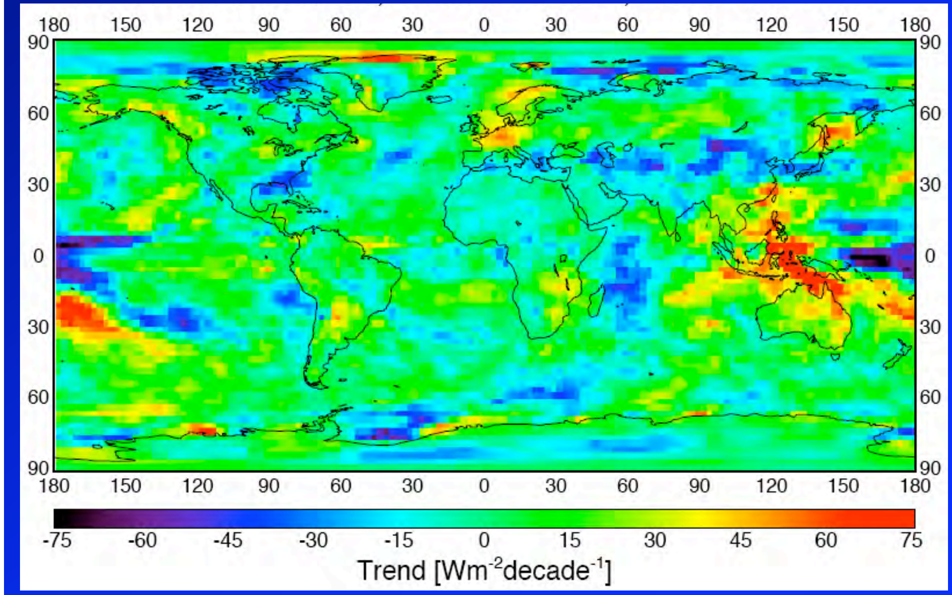
Uncertainty in Geo trends are a factor of 10 larger than climate goal: can we learn how to improve past data sets?



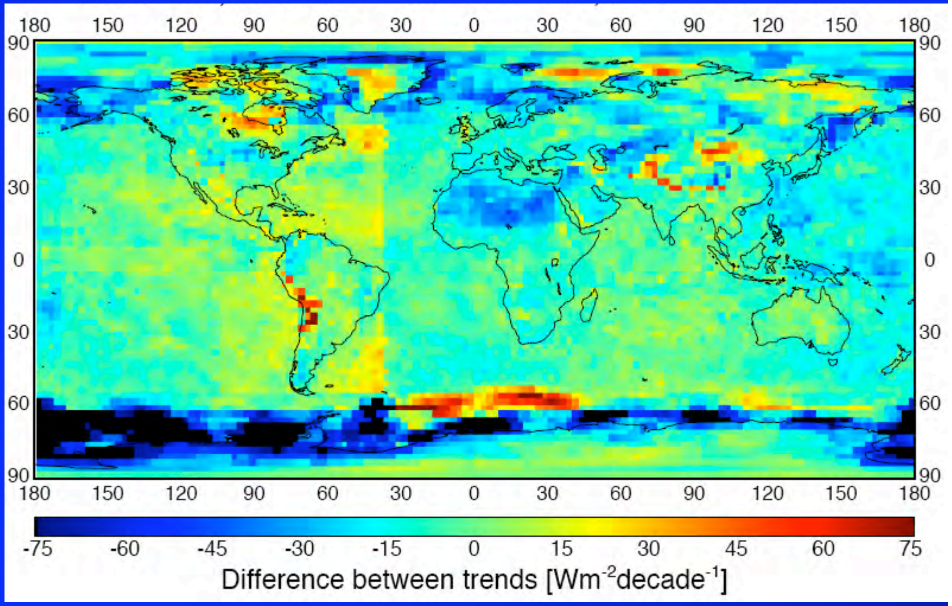
Loeb et al., 2007 J. Climate

Trend in All-sky Downward SW flux at the Surface (2000-2004) ISCCP vs CERES

CERES (SRBAVG_GEO)



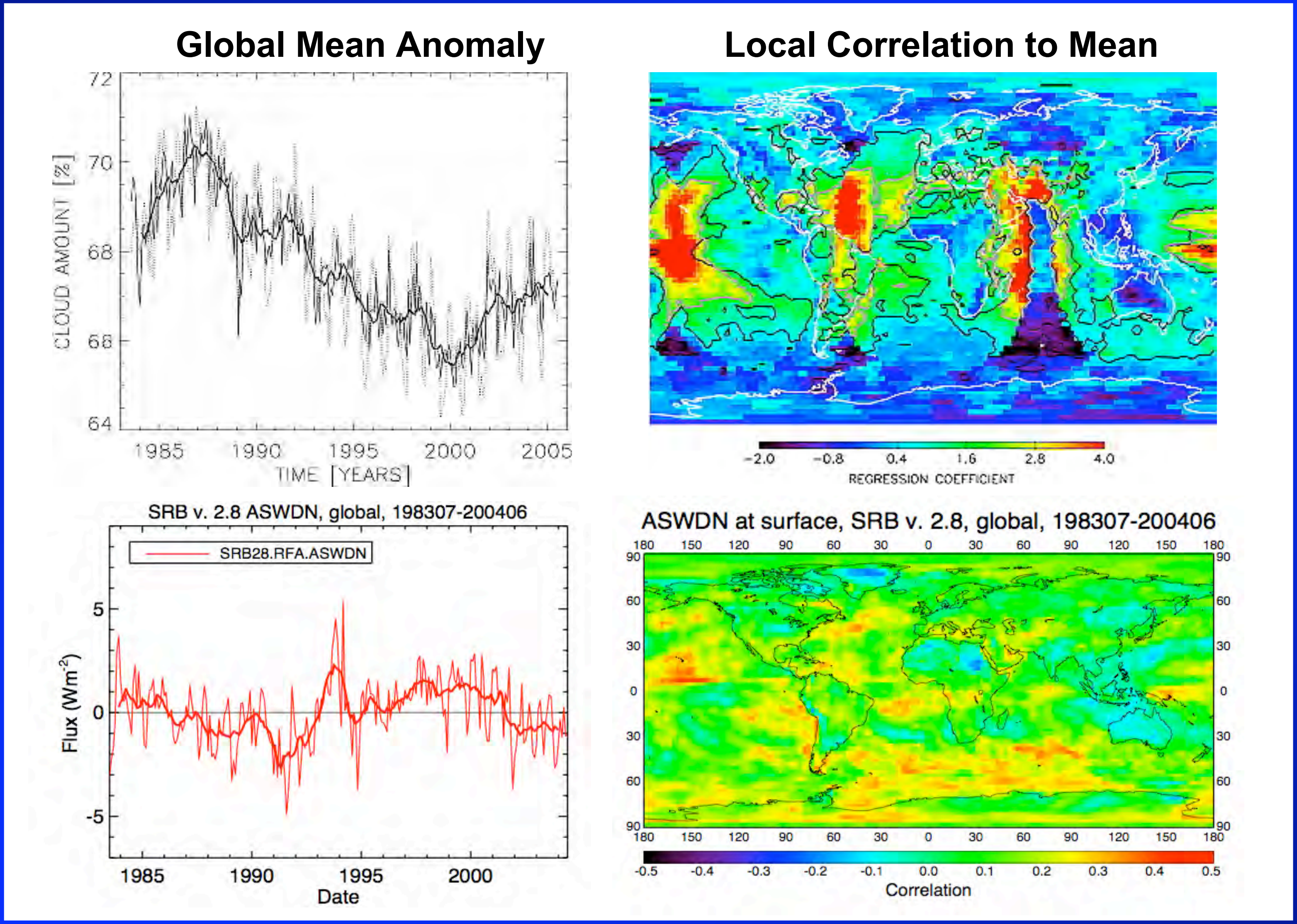
ISCCP minus CERES



- *ISCCP trends show systematic regional patterns that coincide with the area of coverage by the individual GEO instruments.*

- *Artifacts in the GEO data are removed in CERES processing by a normalization procedure that corrects for GEO calibration, narrow-to-broadband, and radiance-to-flux conversion errors, so that fluxes from each GEO instrument are consistent with CERES: suggests that NIST-in-Orbit can work if done carefully.*

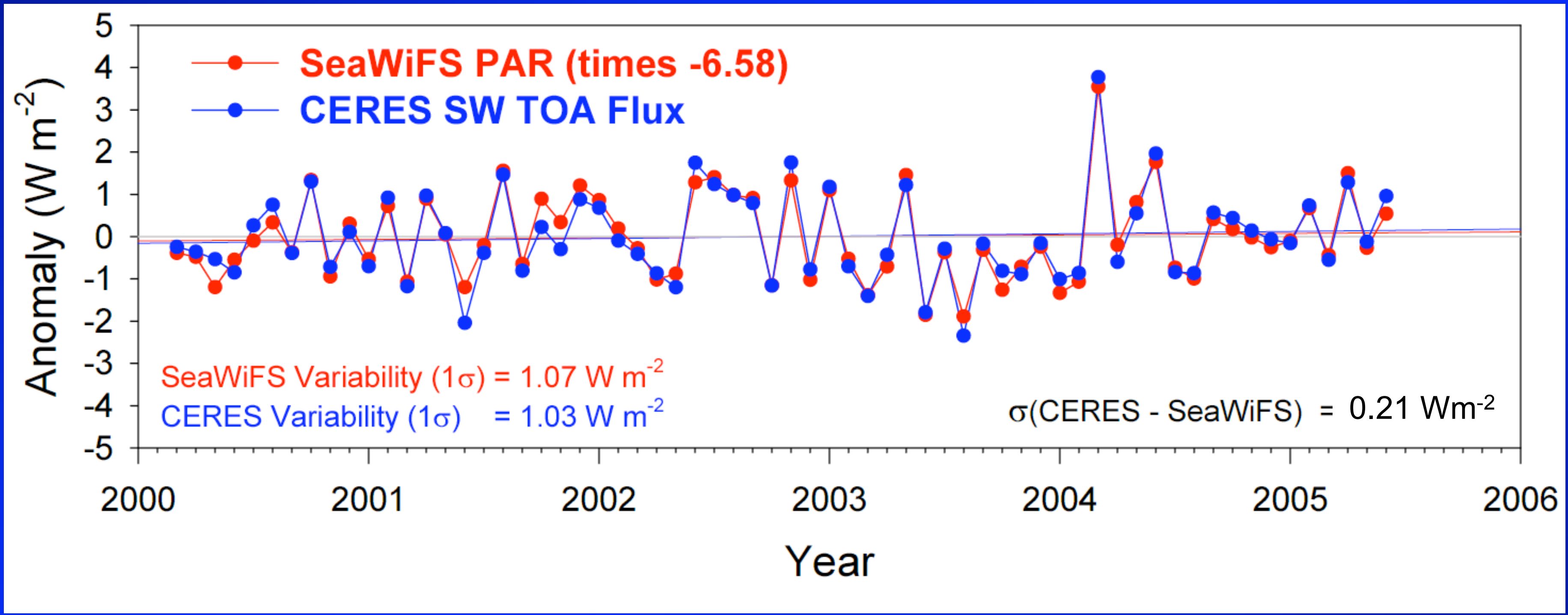
ISCCP Cloud Cover Artifacts



Conclusion: Caused by geostationary viewing angle and calibration inconsistencies. GEWEX Cloud and Radiation Assessments. ***From L. Hinkelman***

Independent Observations: Proving Key Climate Variations

Compare CERES broadband reflected solar flux (calibration, multiple instruments to detect change differences in orbit)
To independent SeaWiFS narrowband PAR (lunar stability, S/C pitchover)

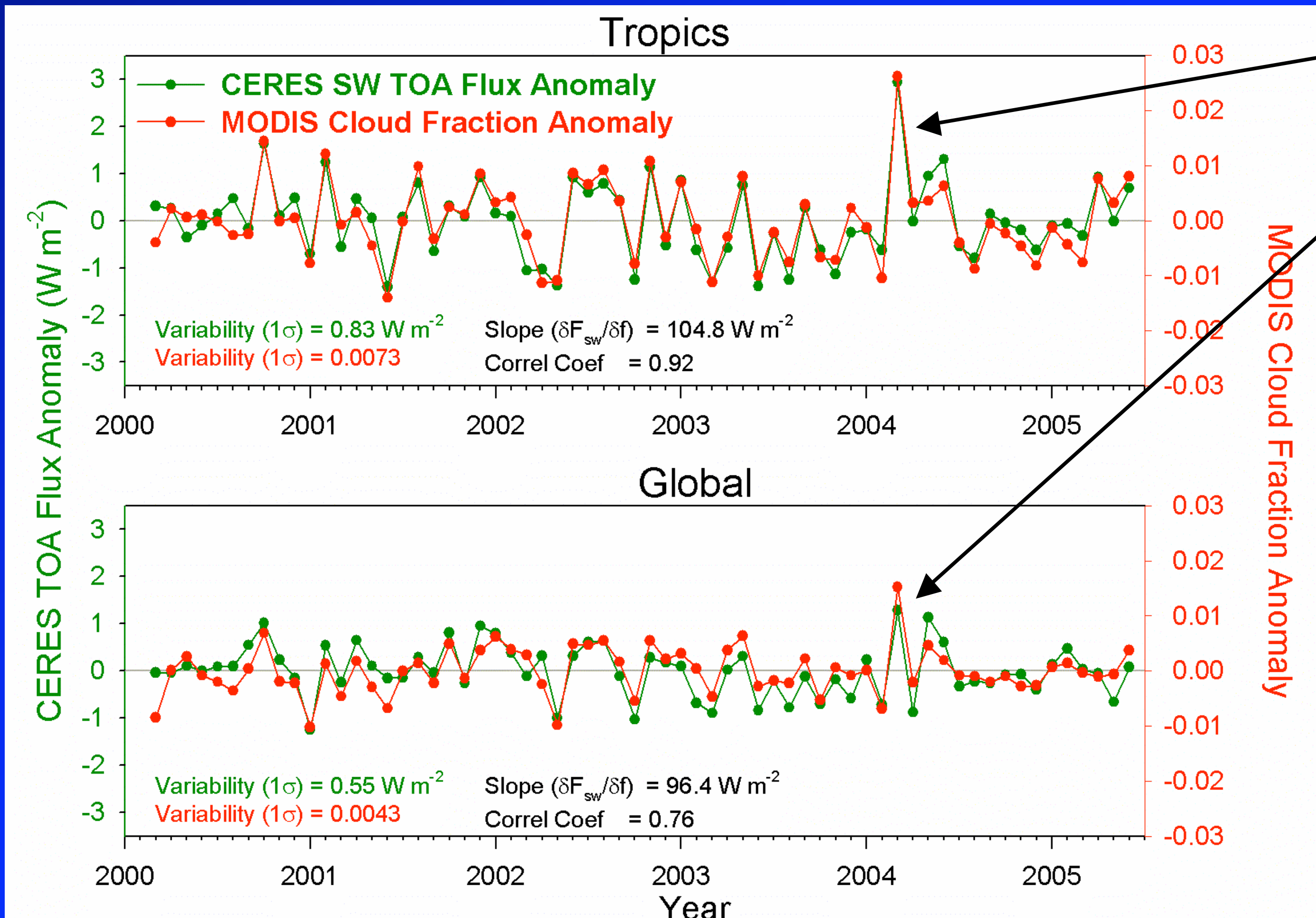


Shows consistent calibration stability at < 0.3 Wm^{-2} per decade (95% conf) climate decadal change accuracy requirements

Comparison is only valid for tropical ocean and simple cloud fraction changes. Aerosol, land, desert, snow, and vegetation all cause 10 times larger narrowband to broadband inconsistencies)

Loeb et al. 2007 J. Climate

What drives changes in global albedo?
How large are they? *The first rigorous determination*



Tropics drives global albedo variations. Global is in phase with tropics and 1/2 the magnitude (CERES flux data)

Cloud fraction variations are the driver. Not optical thickness or cloud particle size. Low cloud changes dominate. (MODIS cloud data)

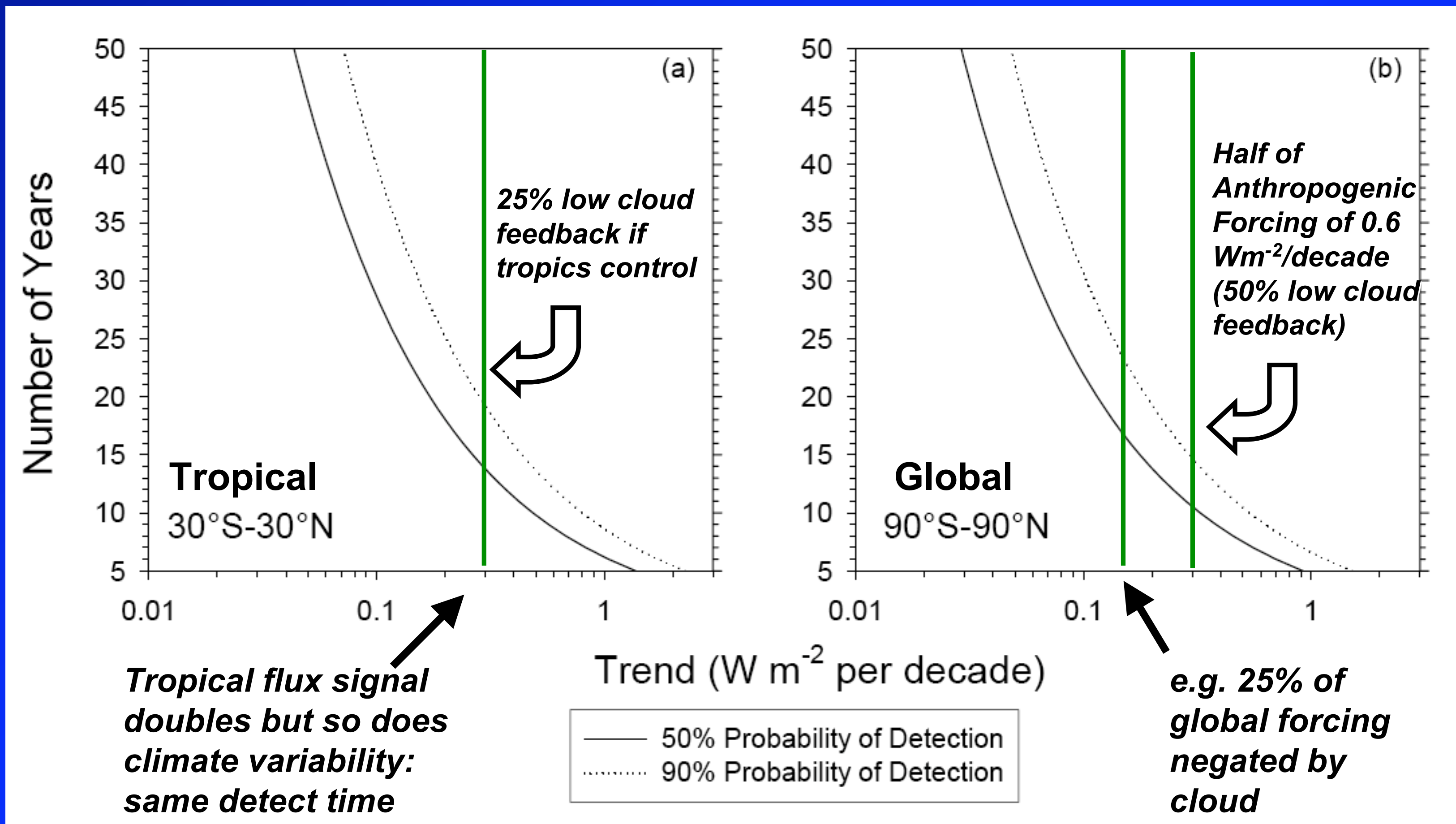
Results are based on combined climate analysis of Terra's CERES radiation budget instruments (2), MODIS cloud and aerosol analysis, snow & ice maps, GEOS 4.0.3 weather assimilation for temperature/humidity for climate applications. Note: 0.3 albedo ~ 100 Wm^{-2} reflected shortwave flux

Loeb et al., GRL (2007)

IPCC AR4 Report: Low Cloud Feedback Largest Uncertainty

How long to observe a 25% low cloud feedback?

For low clouds: Earth reflected solar flux dominates the feedback

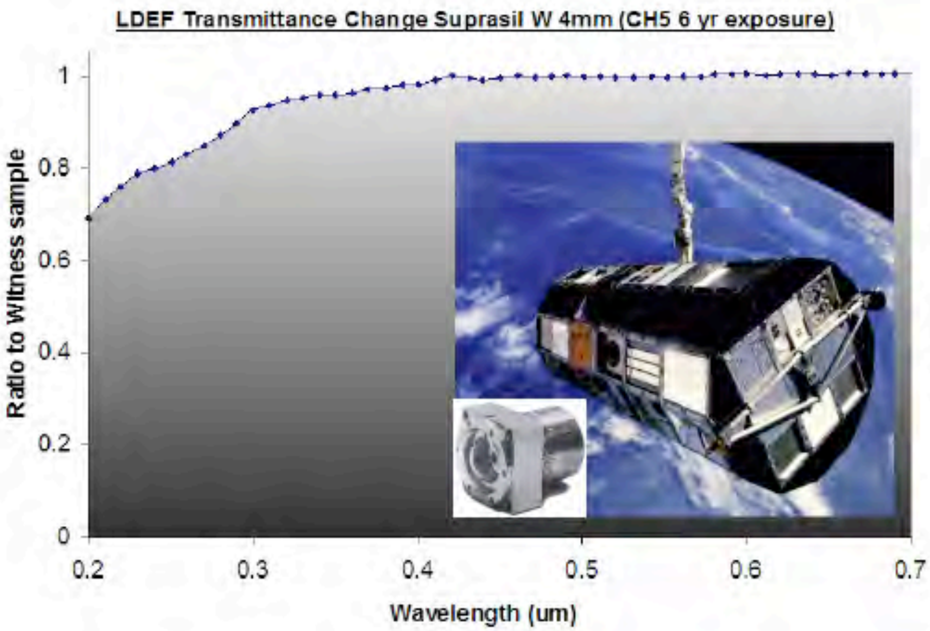


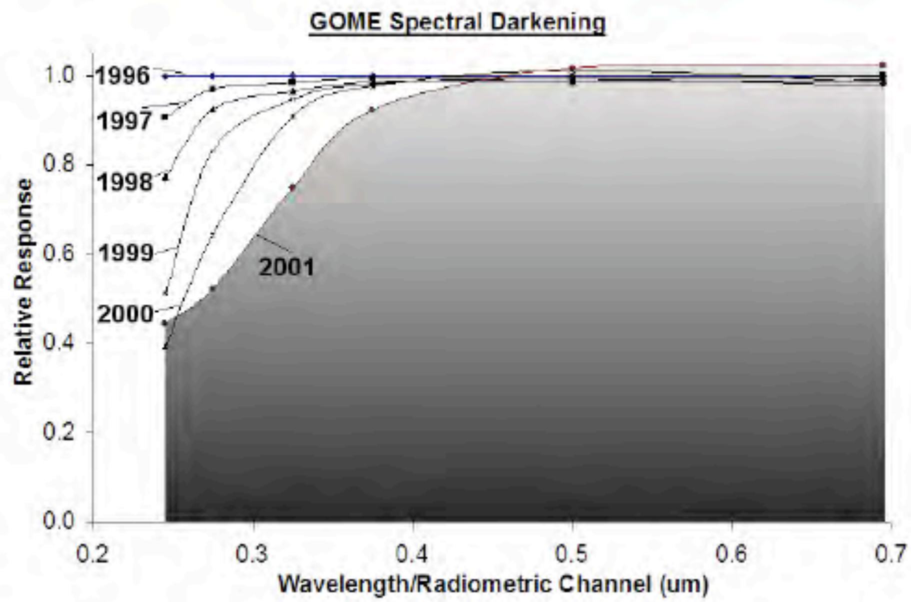
Given climate variability, 15 to 20 years is required to detect cloud feedback trends with 90% confidence. Loeb et al. J. Climate, 2007

Requires cloud radiative forcing calibration stability of 0.3% per decade

Evidence for Solar Optics Contamination in Orbit: Especially below 0.5μm wavelength

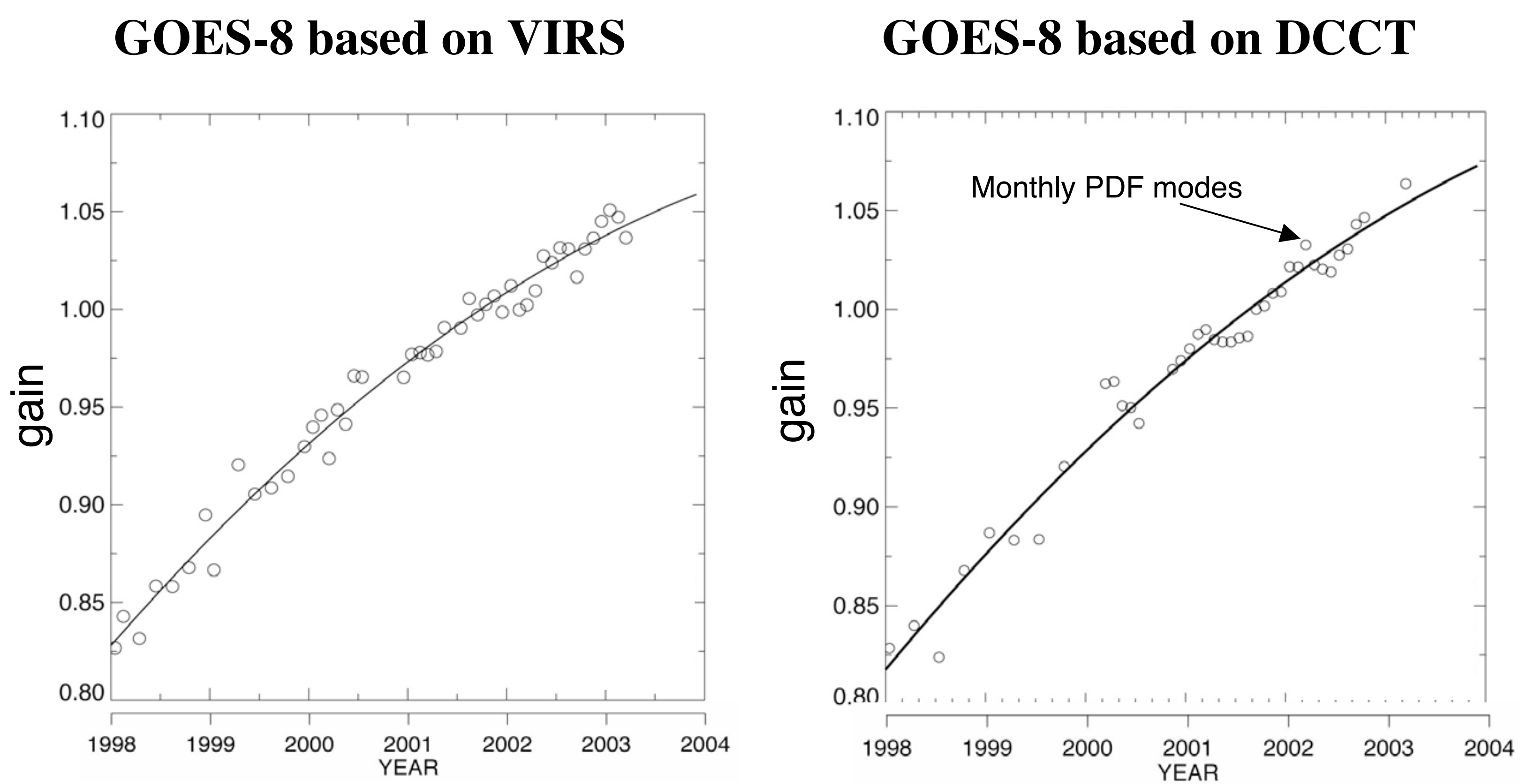
This matches the shape of spectral darkening occurring on LDEF and GOME:





Conclusion: It is critical to provide spectrally dependent calibration to reach climate accuracy for solar reflectance. From G. Matthews, 2007

Comparison of LEO-GEO Intercalibration and that using Deep Convective Clouds: Detector Gain Change



D. Doelling

Conclusion: Changes of visible channel calibration can be 3 to 5% per year, and normal methods reach consistency of ~ 2 to 3%, a factor of 10 larger than that sought for climate change ~ 0.2%

So how do we reach climate accuracy?

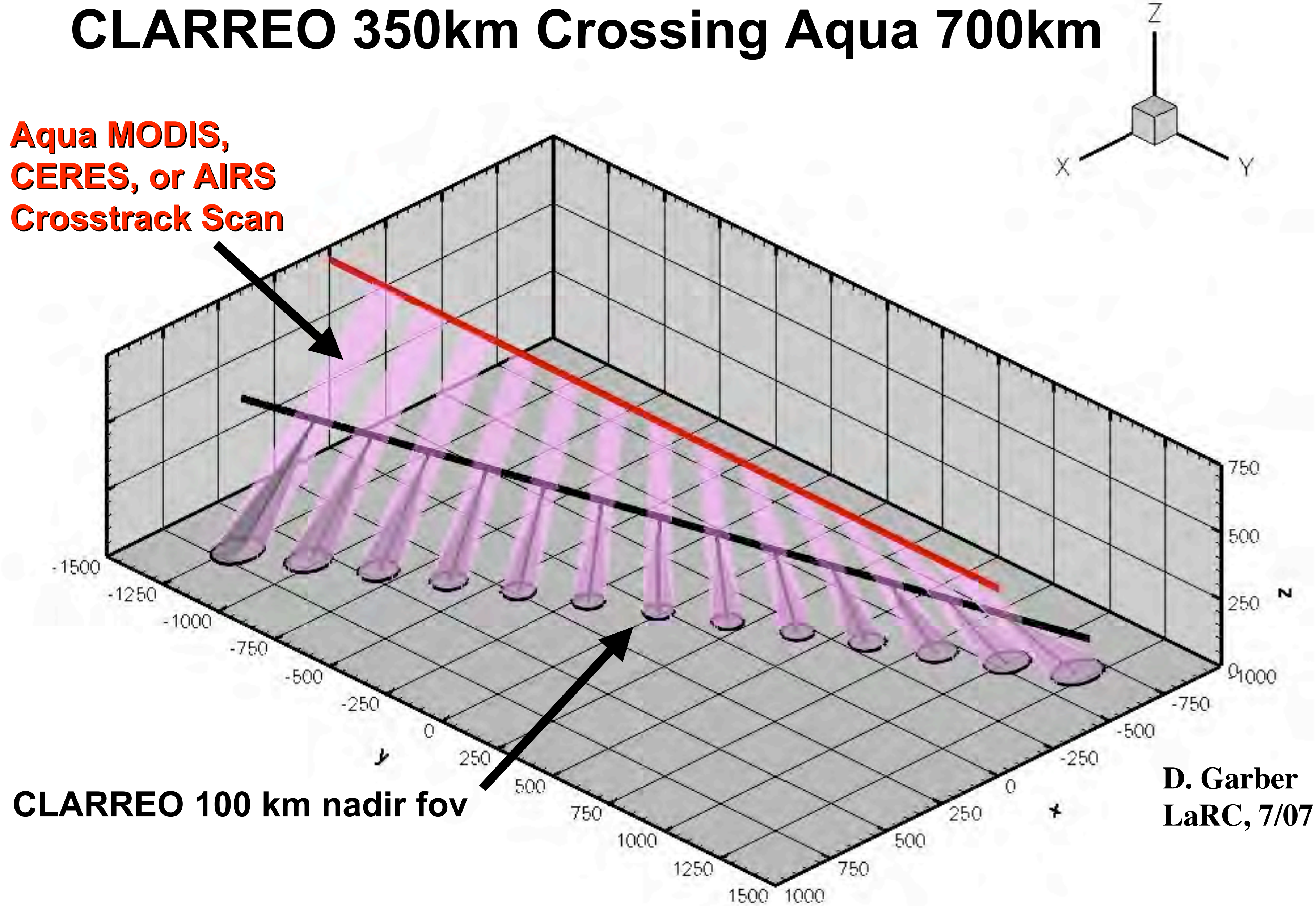
- One way is to make all instruments at climate accuracy of 0.2% solar reflectance, and 0.1K infrared. Much more effort, mass, power, put into on-board calibration sources. NPOESS VIIRS imager will be less well calibrated than MODIS.
- Fly multiple copies of all instruments (like CERES on Terra/Aqua) to independently confirm surprises.
- Do lunar calibration pitchovers like SeaWiFS (~ monthly) to verify against more stable targets like the moon (NPOESS, NPP and Aqua refuse, Terra did it once, TRMM 6 times).
- CLARREO suggests that a better and more cost effective approach is to fly benchmark solar and infrared spectral radiance records in space: how could these be used to calibrate the other instruments in orbit?

Radiation and Calibration are 8-dimensional Sampling Problems

- Latitude
- Longitude
- Altitude
- Time
- Solar Zenith Angle
- Viewing Zenith Angle
- Viewing Azimuth Angle
- Wavelength

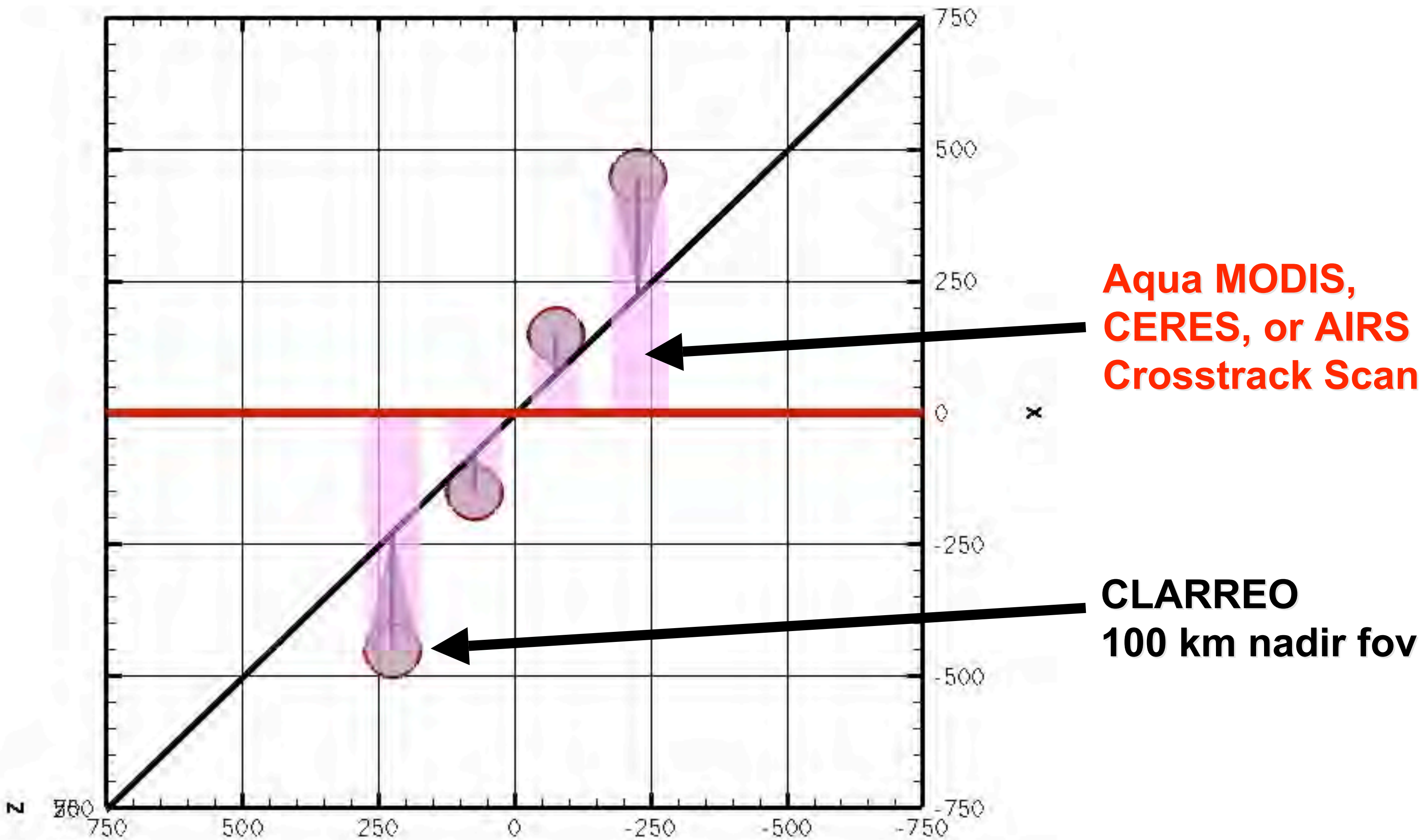
- Radiance signals vary a factor of 2 to 10 with all of these dimensions. Yet key climate change is a few tenths of a percent/decade.
- Climate Change adds a stealth "9th dimension": accuracy

CLARREO 350km Crossing Aqua 700km



Time to Achieve Viewing Angle Matches:
40 seconds per 100km orbit altitude Difference: 140 seconds above

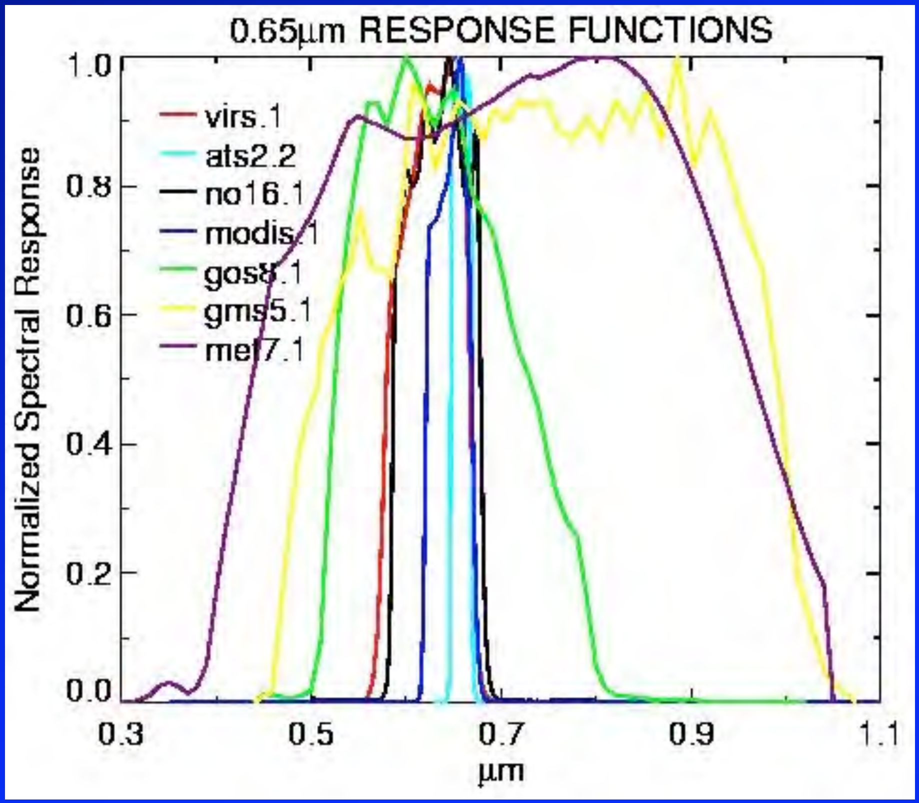
Top View: CLARREO 350km, Aqua 700km

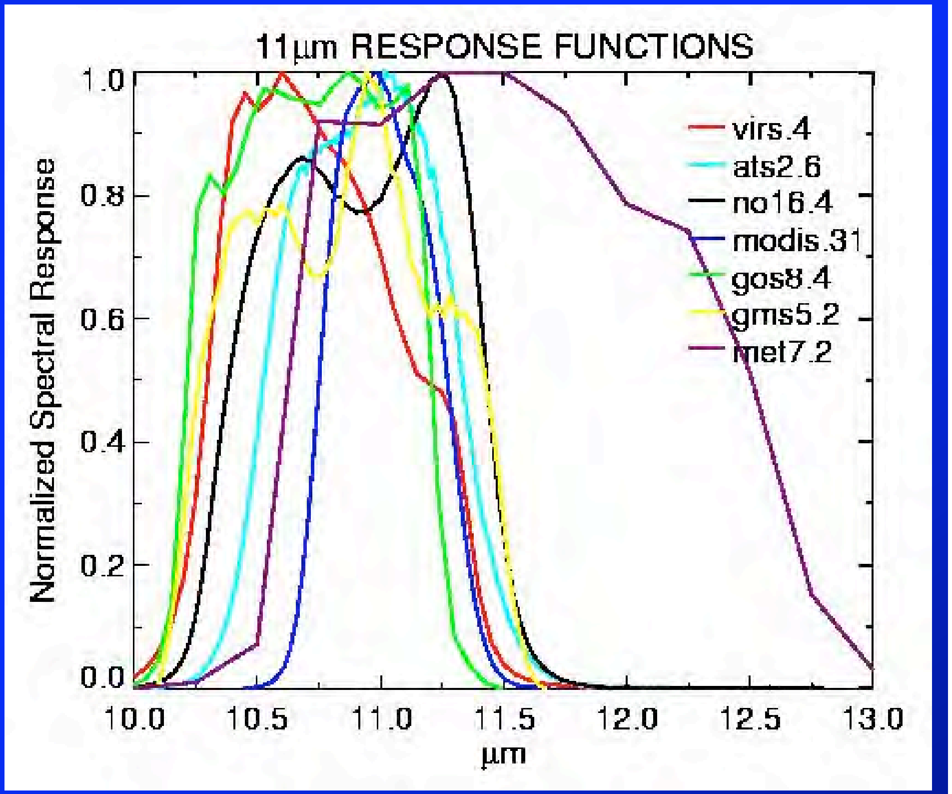


Angle Pointing (zenith, azimuth) is required to obtain any calibration matches beyond those at nadir. Options: pointable instrument, pointing table, or S/C reaction wheels

D. Garber
LaRC, 7/07

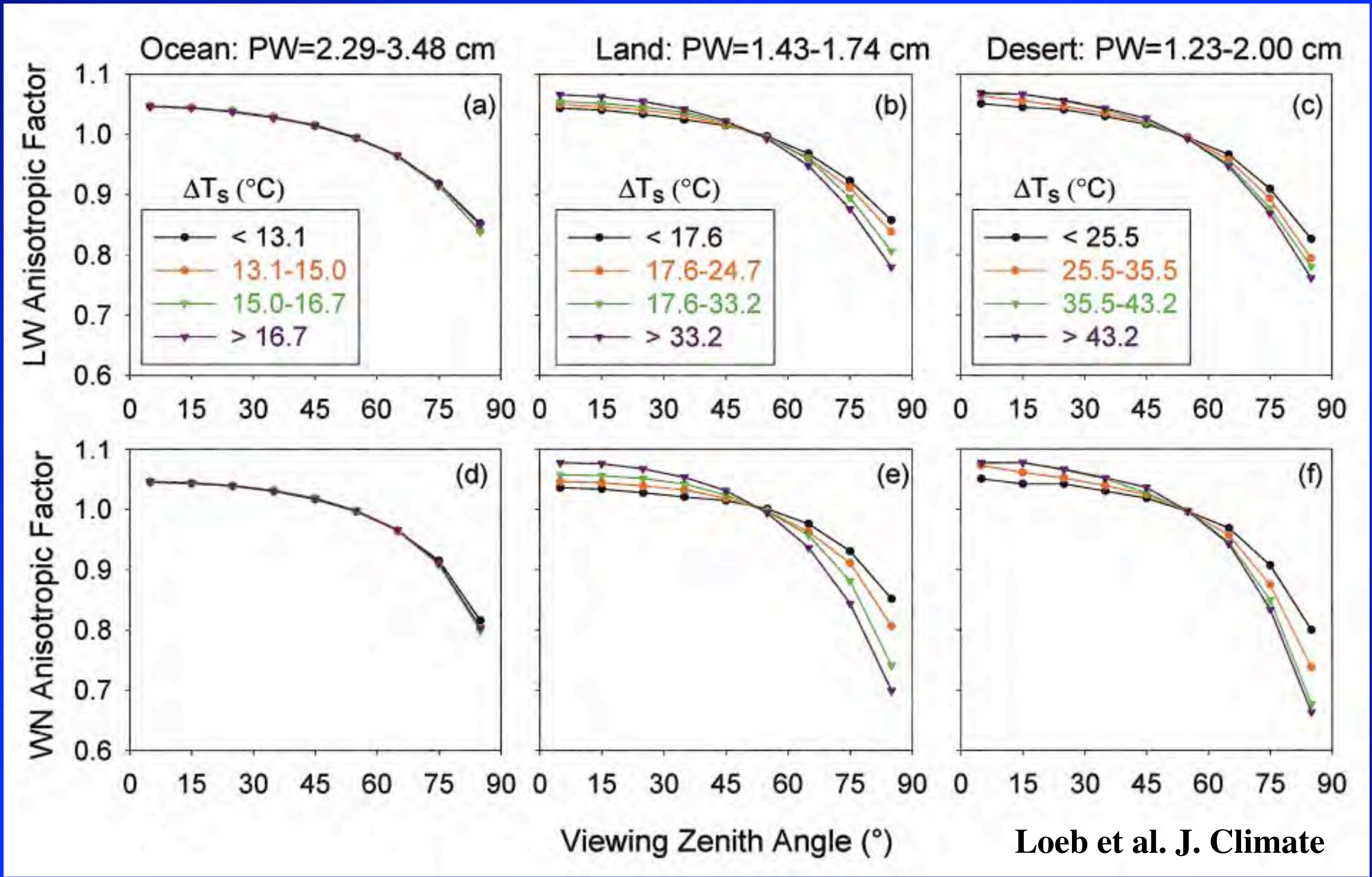
0.65µm & 11µm Channel Spectral Response Functions Vary Greatly





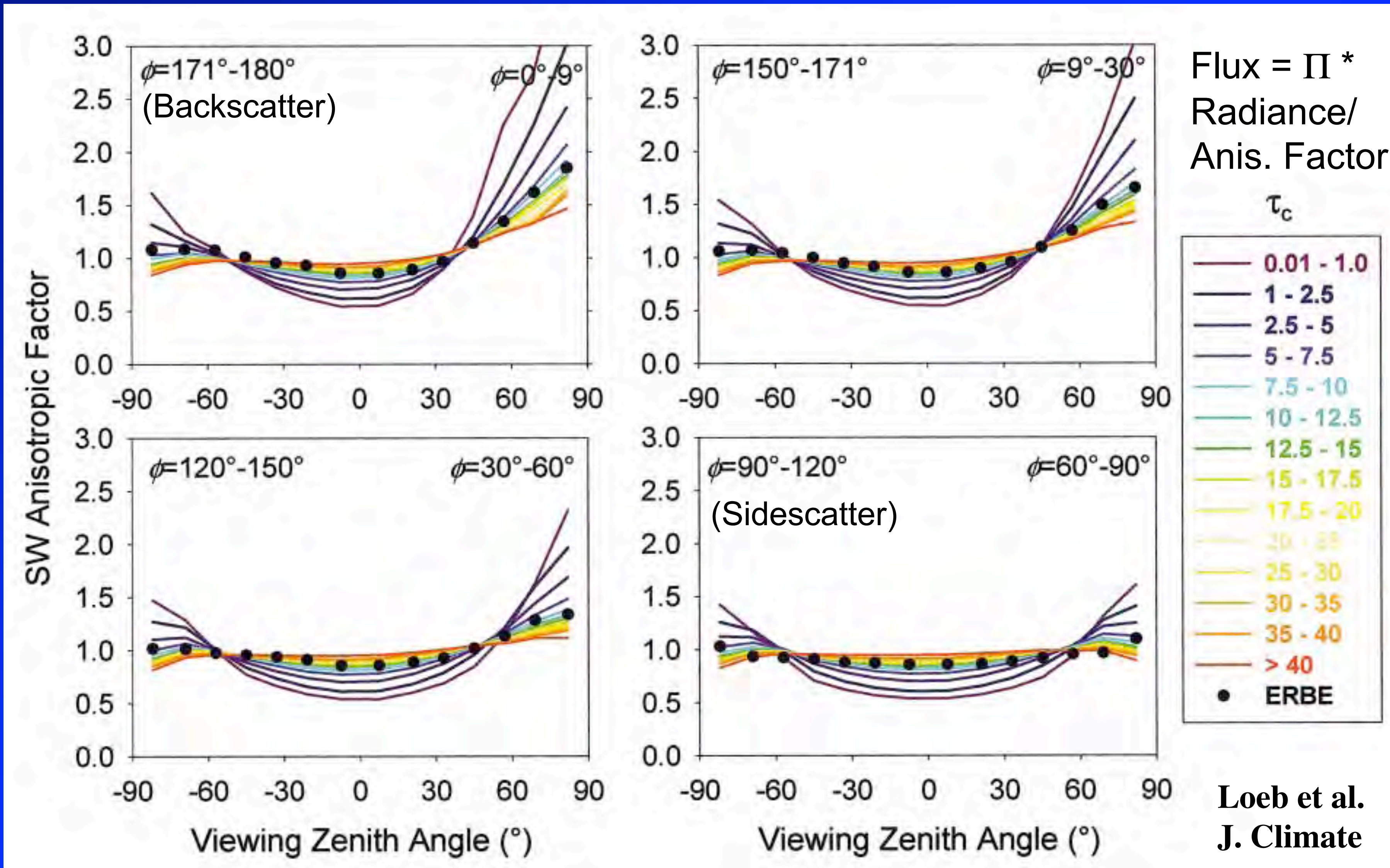
Similar variations seen in other channels..

Infrared Anisotropy: Radiance to Flux Ratio



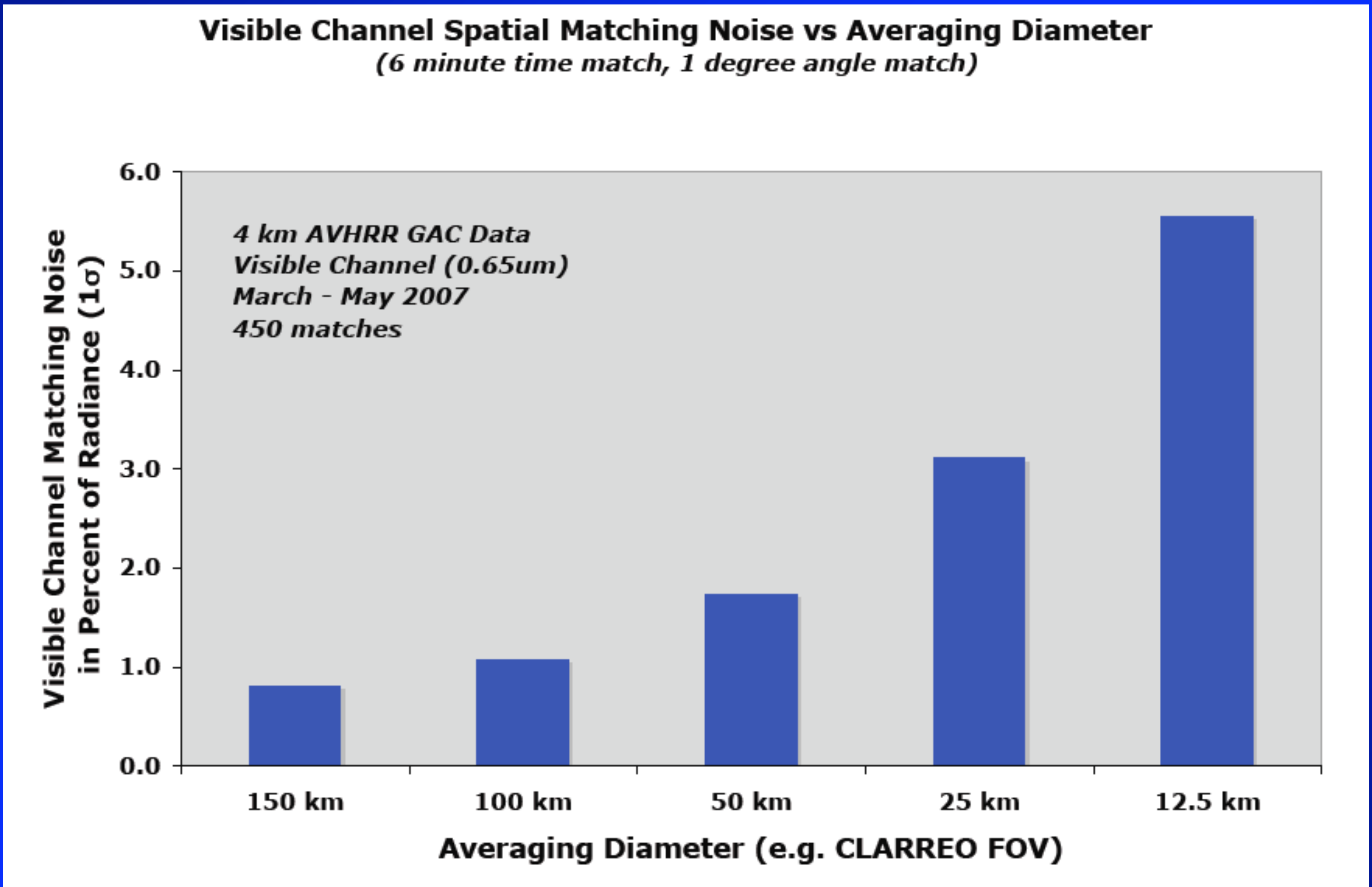
Typical Broadband Longwave Anisotropic effect is ~ 5 to 10%
Typical Atmospheric Window (WN) Anisotropic effect is ~ 10 to 20%.

Solar Reflected Anisotropy: Radiance to Flux Ratio



Typical Broadband Shortwave Flux Anisotropic effect is ~ 50 to 200%.
Factor of 10 larger anisotropy issues in solar reflected observations than IR.

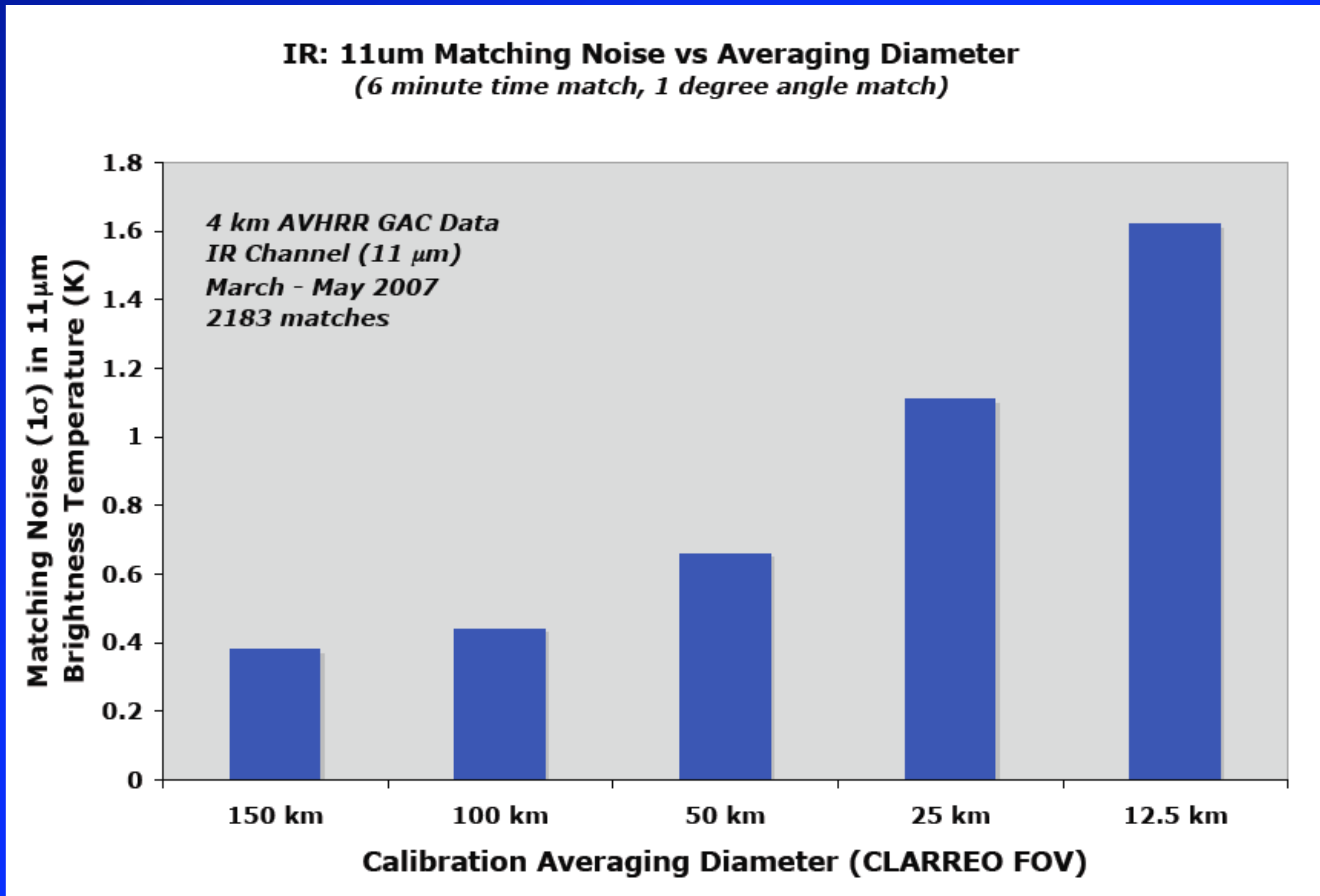
How Does Field of View Affect Matching?



D. Doelling

Conclusion: 50 to 100km field of view needed to reduce noise.

How Does Field of View Affect Matching?



D. Doelling

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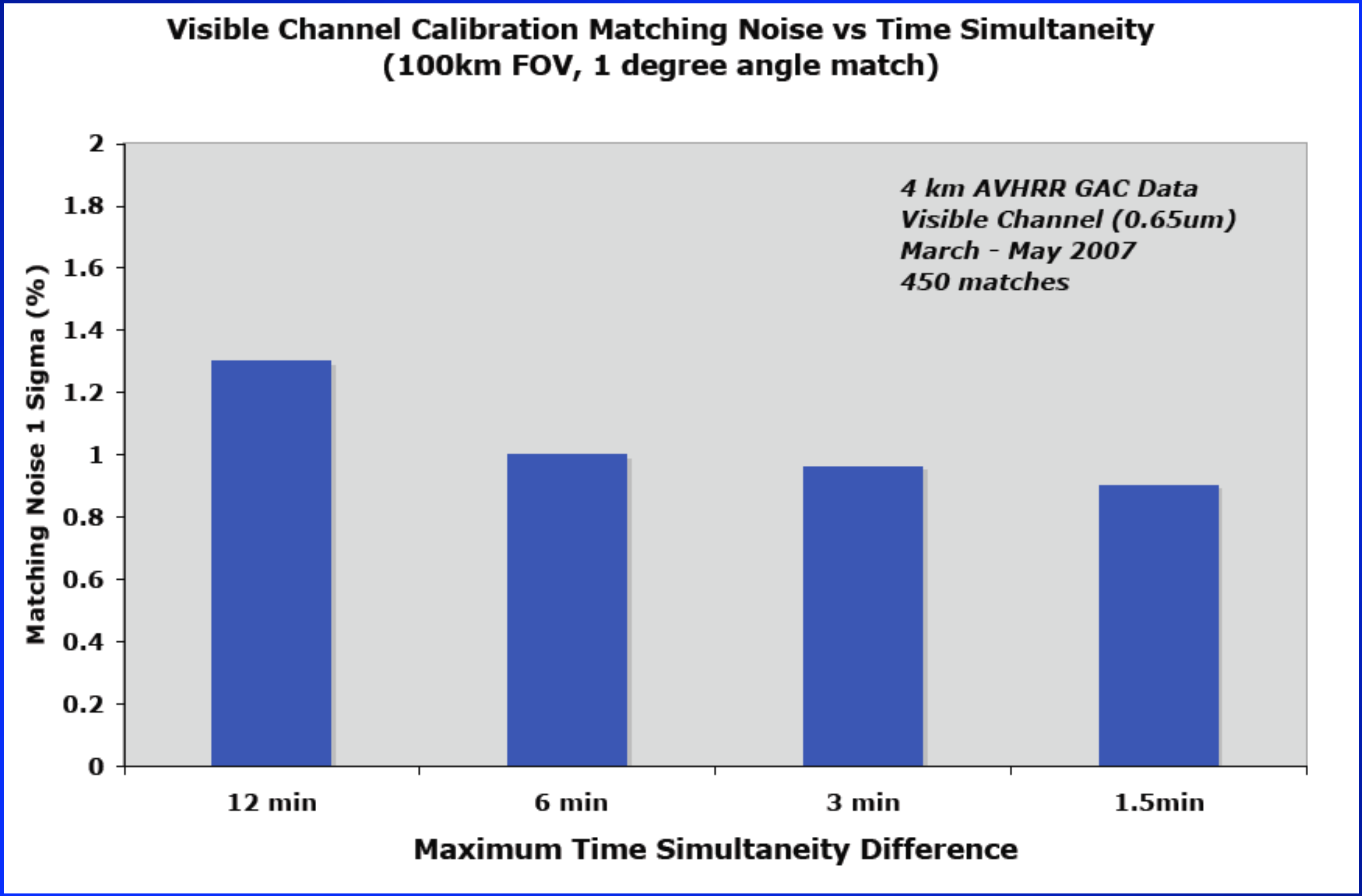
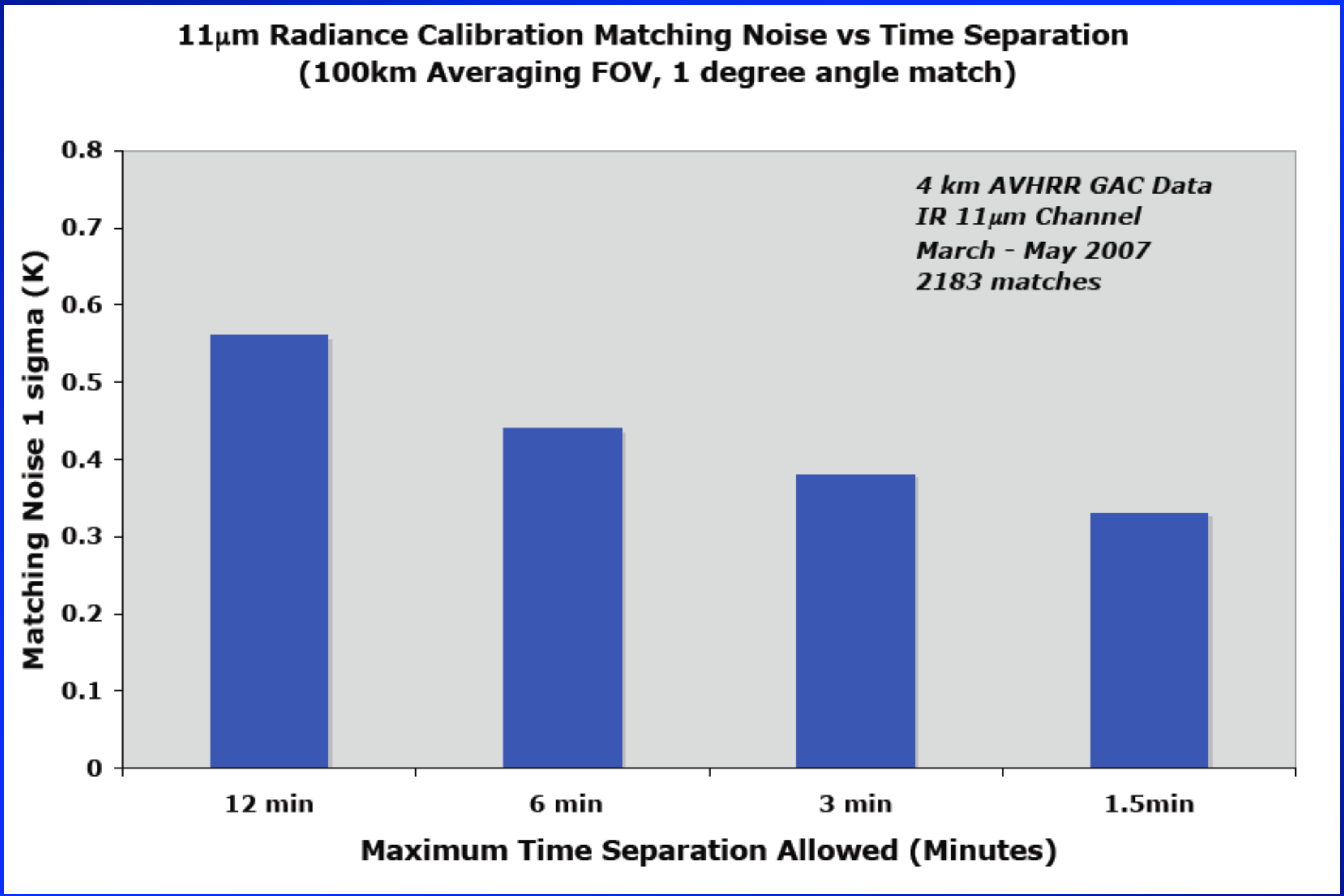
How Does Time Simultaneity Affect Matching?



Conclusion: At 100km fov, 6 minute time simultaneity is sufficient

How Does Time Simultaneity Affect Matching?



Conclusion: At 100km fov, 6 minute time simultaneity is sufficient

Influence of Angle Mismatch in Satellite Instrument Intercalibration

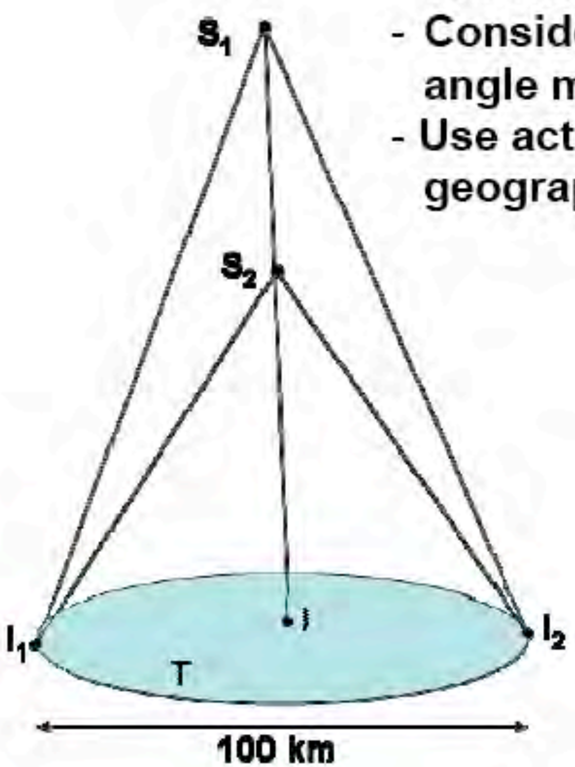
- Over a given region, satellite angle sampling depends upon satellite altitude:

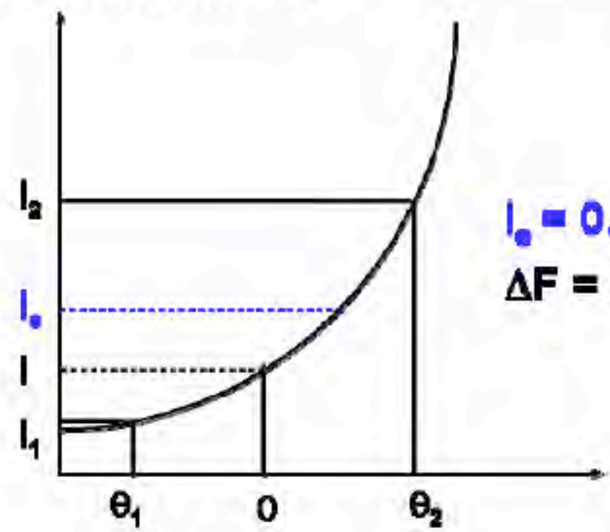
=> For a satellite at 750-km: angle range over 100-km region is $\pm 4°$ (about nadir)

For a satellite at 350-km: angle range over 100-km region is $\pm 8°$ (about nadir)

- Assuming satellite views are aligned in the center of the region, what is the impact of angle mismatches in other portions of the region?

- Assume $S_1 >> S_2$ (worst case scenario).
- Use CERES ADMs to infer I_1, I_2 and I at S_2.
- Consider variations in both θ and ϕ for 2°, 4° and 6° angle mismatches.
- Use actual CERES data (5 days) to get representative geographical scene distribution.

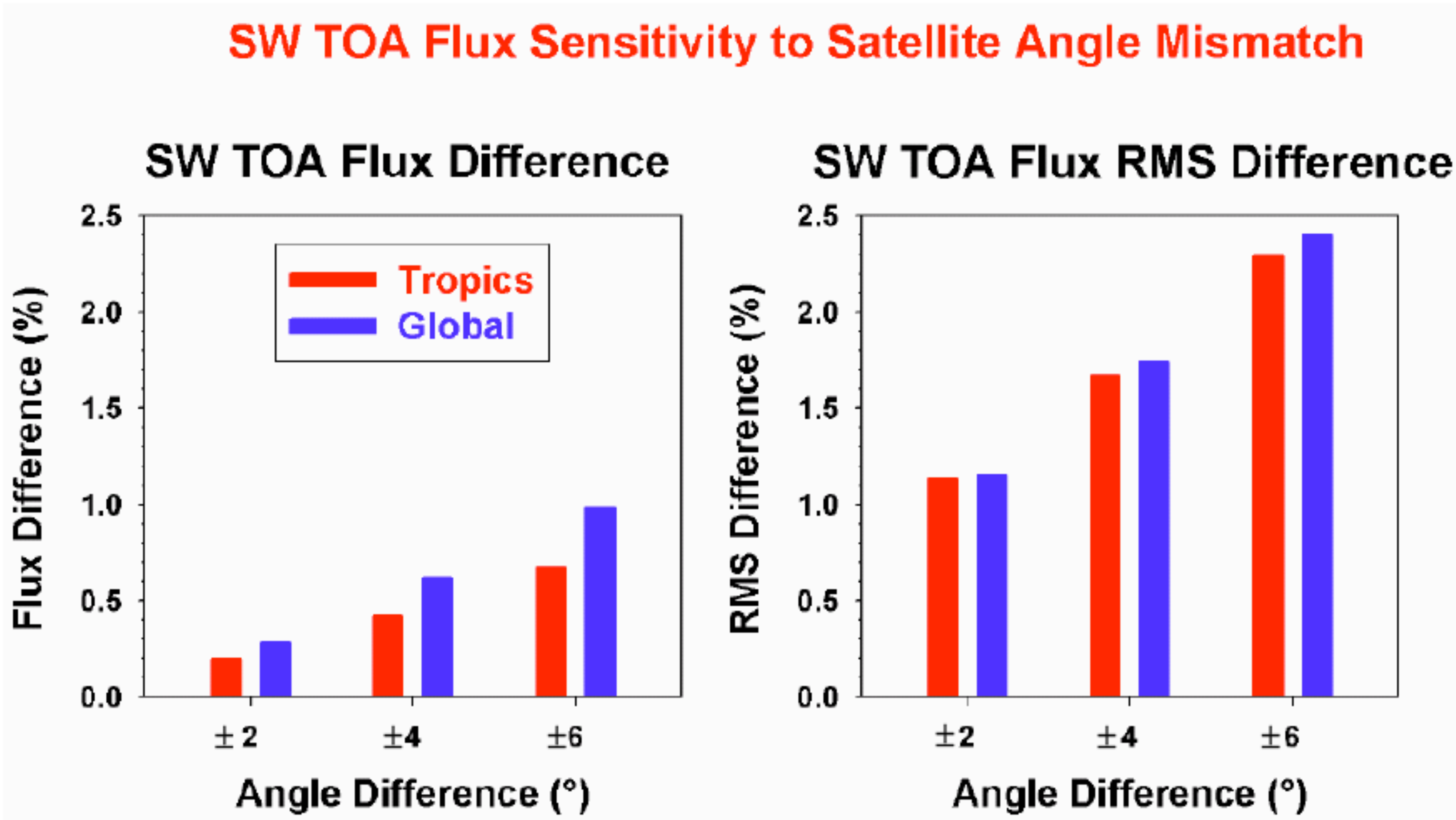




$I_e = 0.5\ (I_1+I_2)$

$\Delta F = \pi\ (I_e - I)\ /\ R$

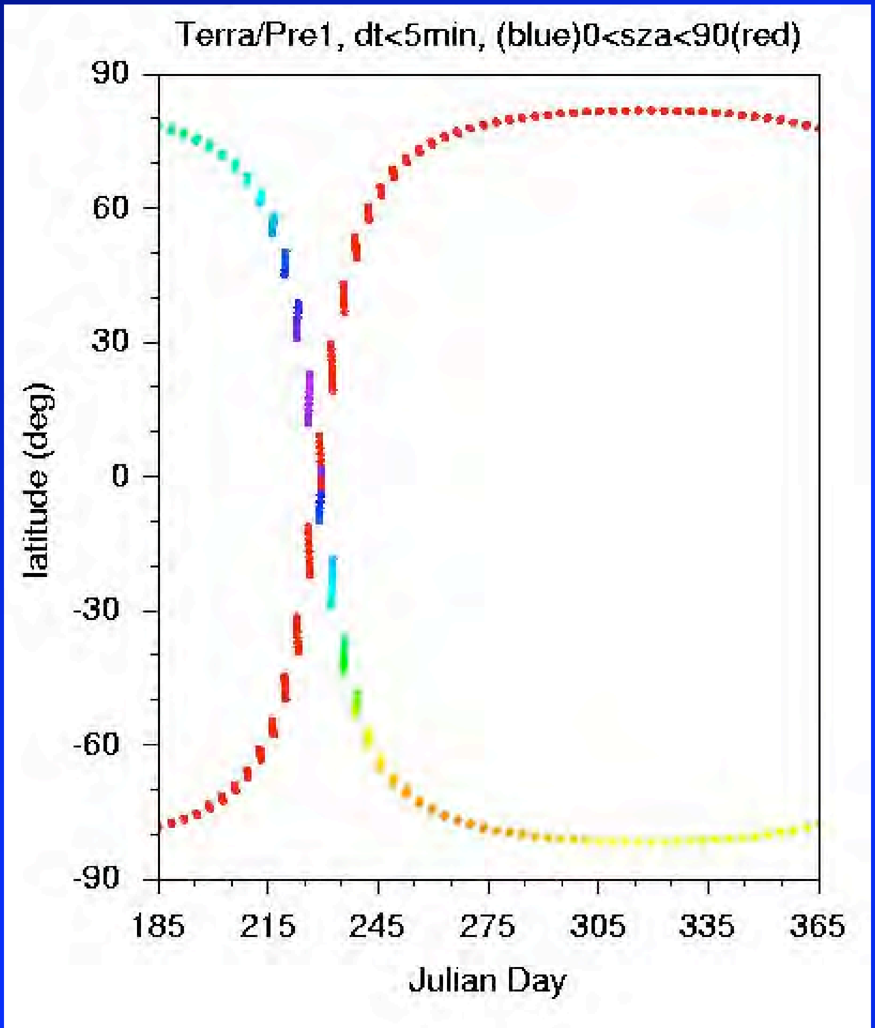
How Close in Viewing Angle to Calibrate?



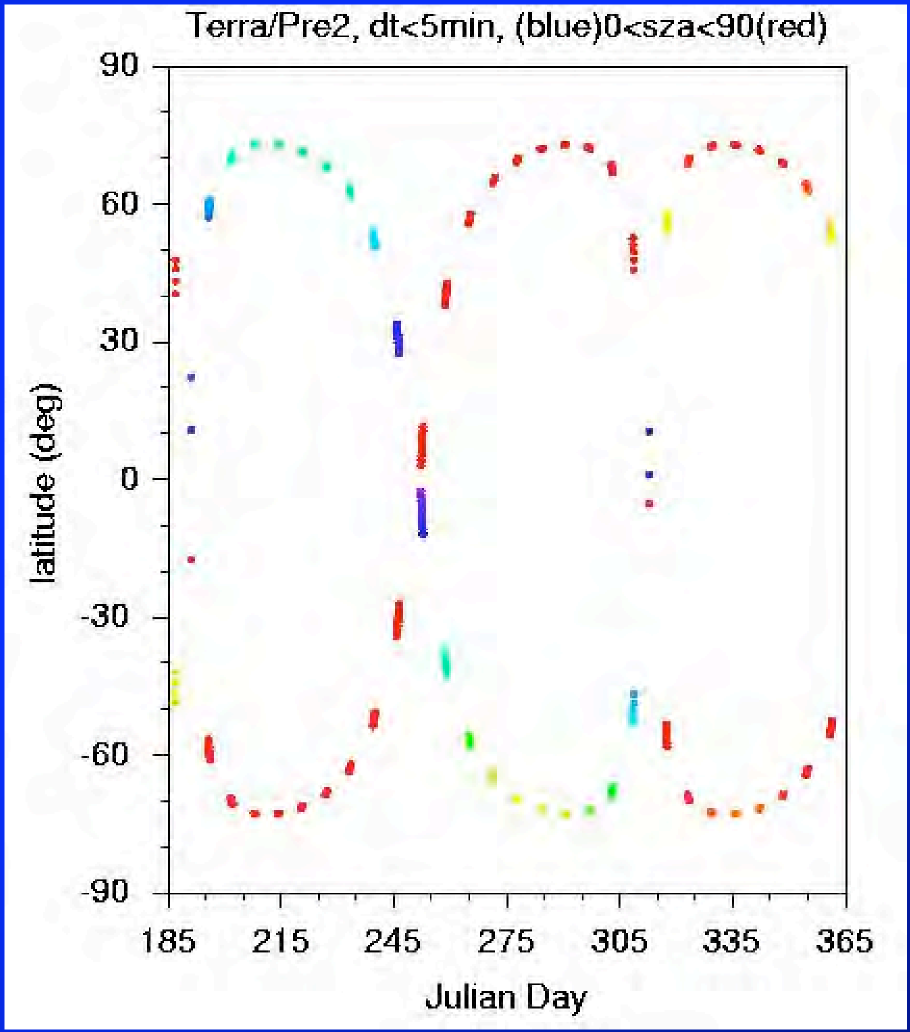
Conclusion: Close angle matching is critical for bias and noise.

How often and Where will Orbits Cross? June - Dec CLARREO calibrating Terra/Aqua/NPOESS

90 degree Incl. 1 24-hr cycle/yr



74 degree Incl. 2 24-hr cycles/yr



Conclusion: intercalibration in polar regions is common for leo satellites, tropics less common: precession cycle limits.

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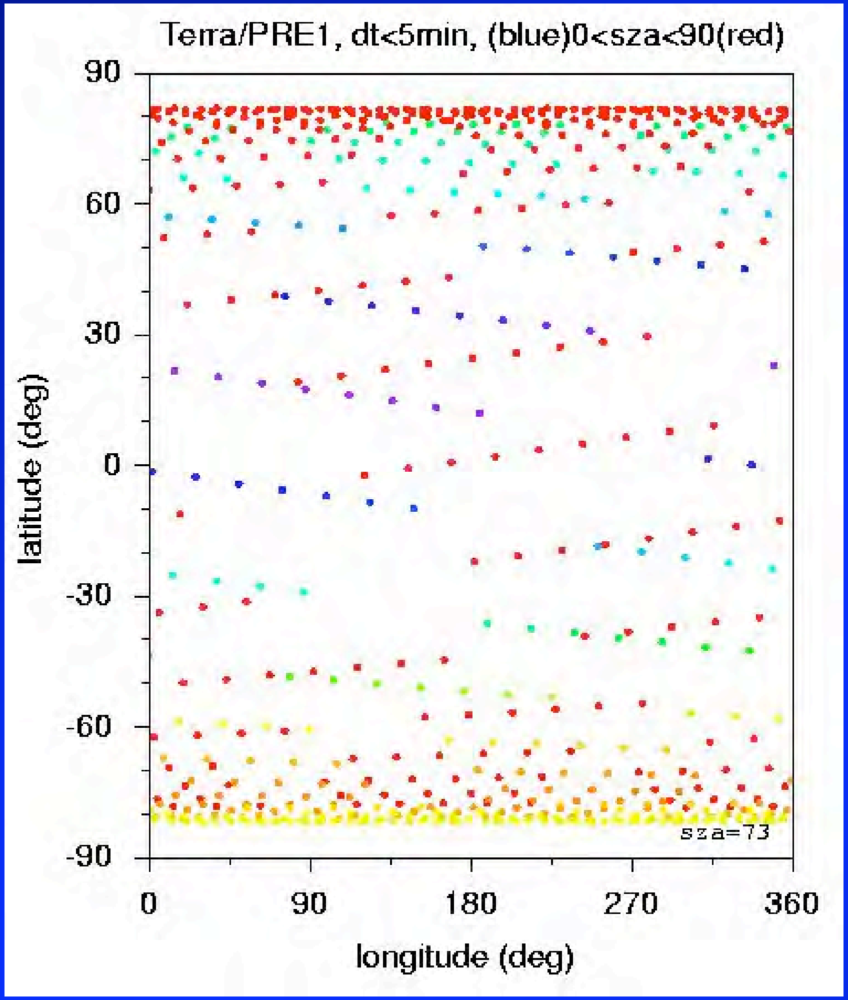

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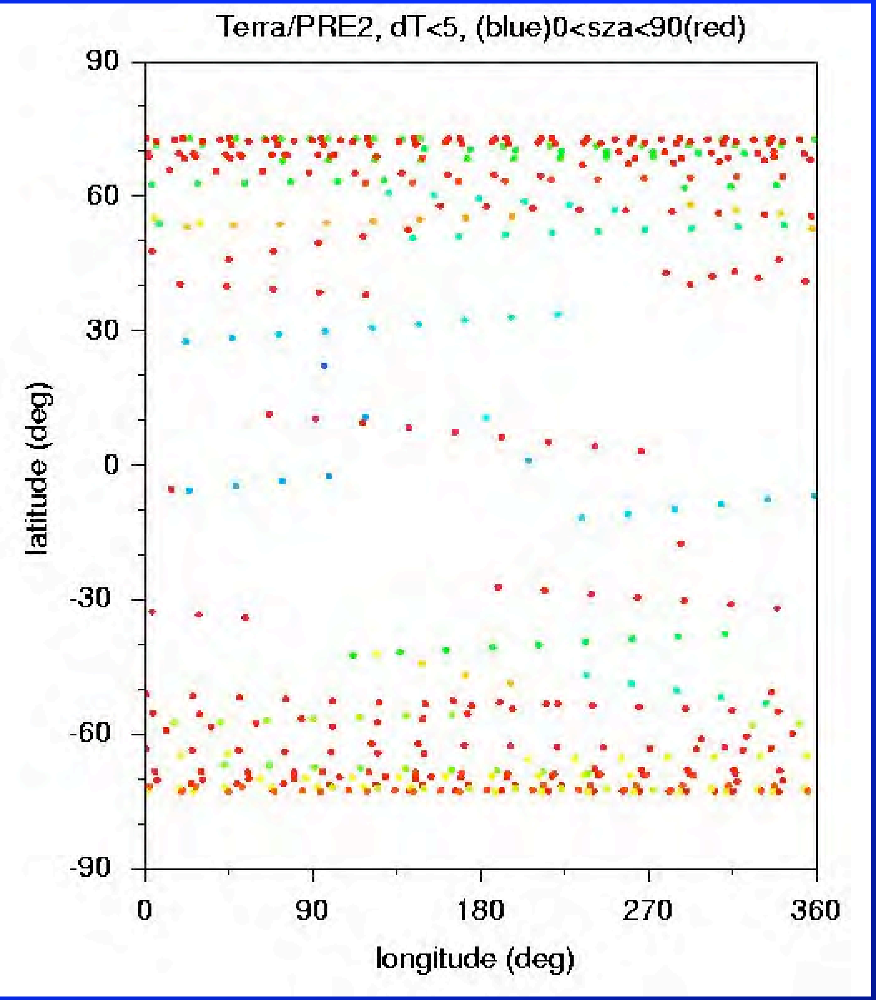
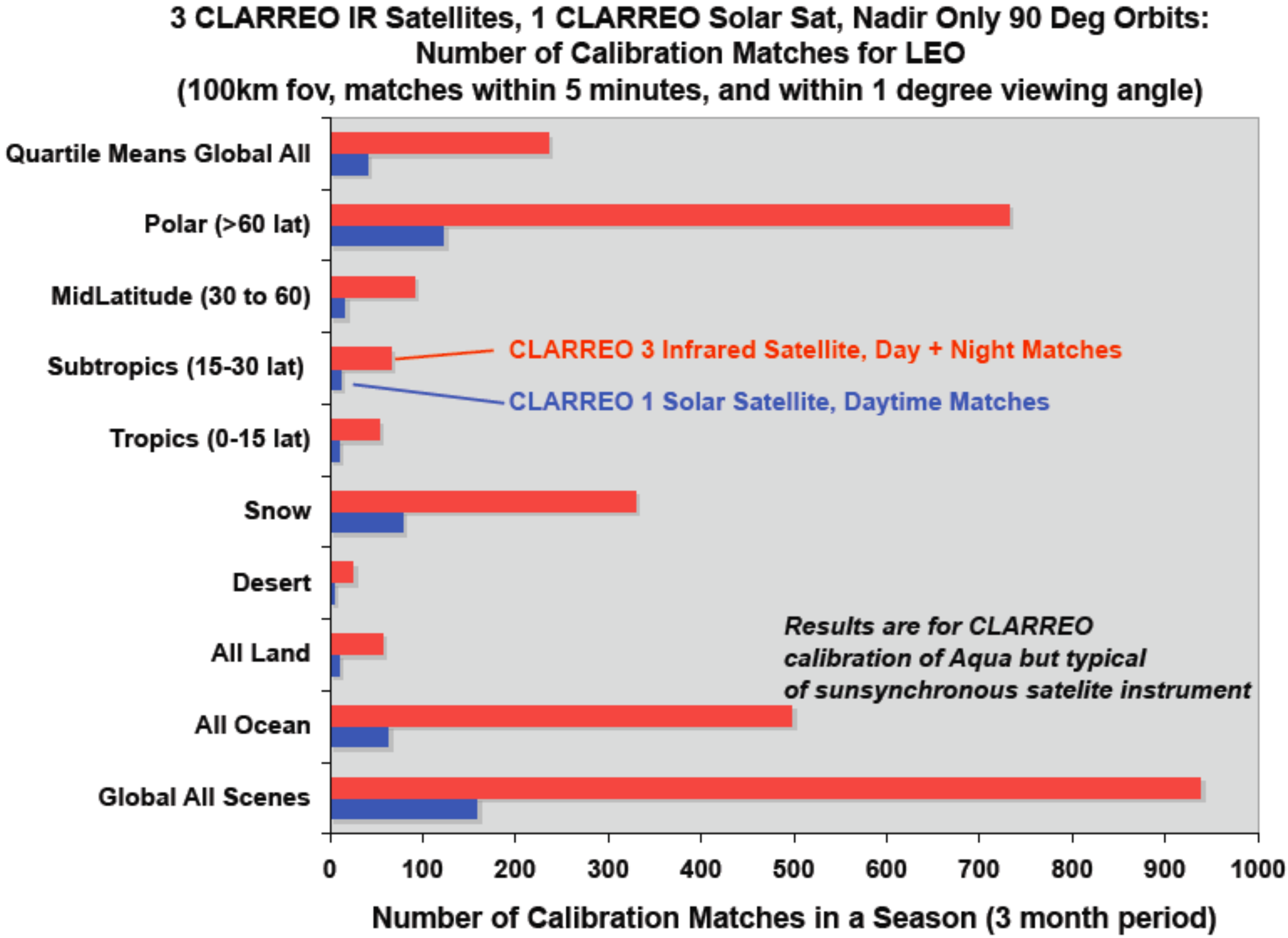
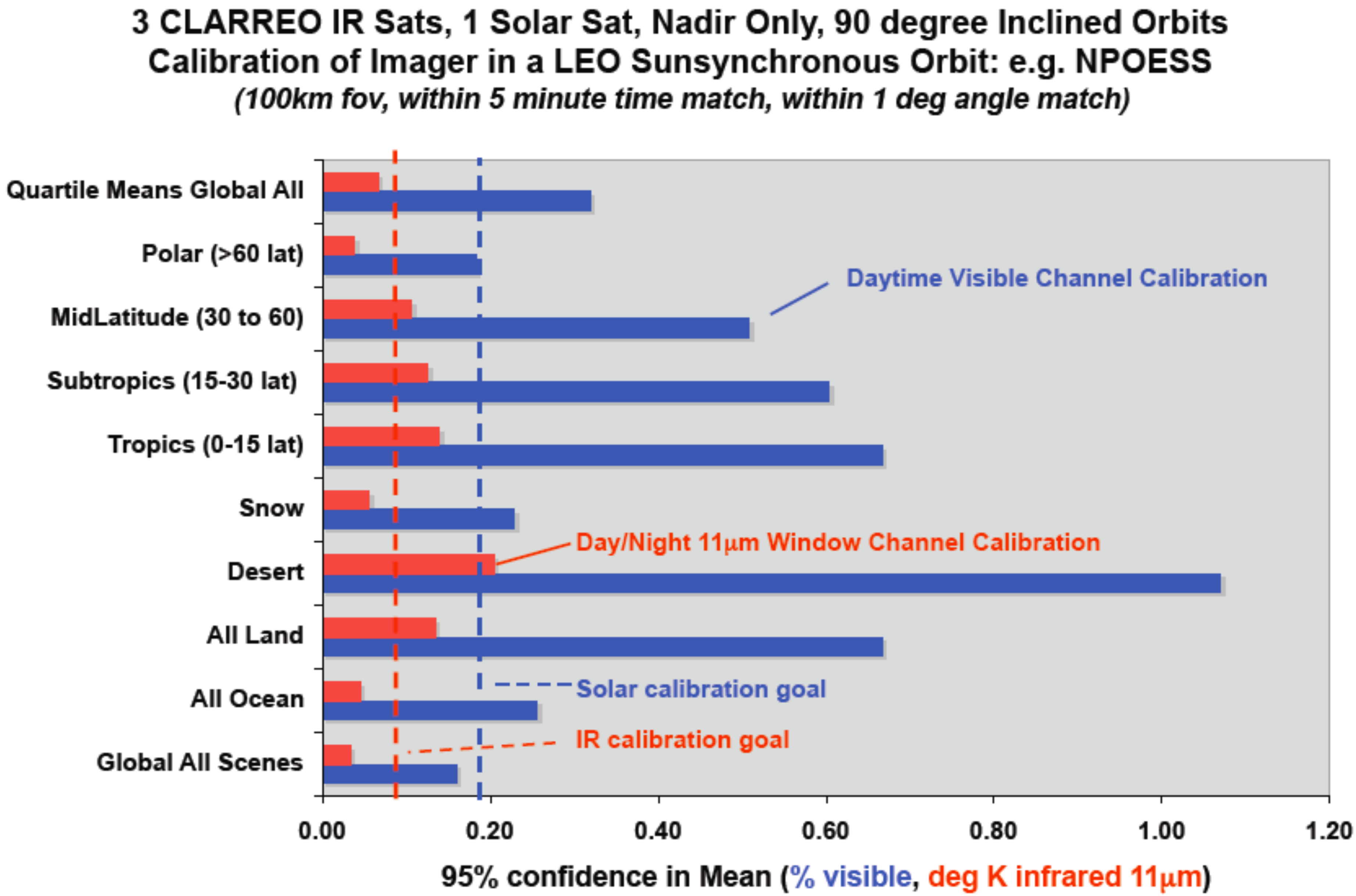


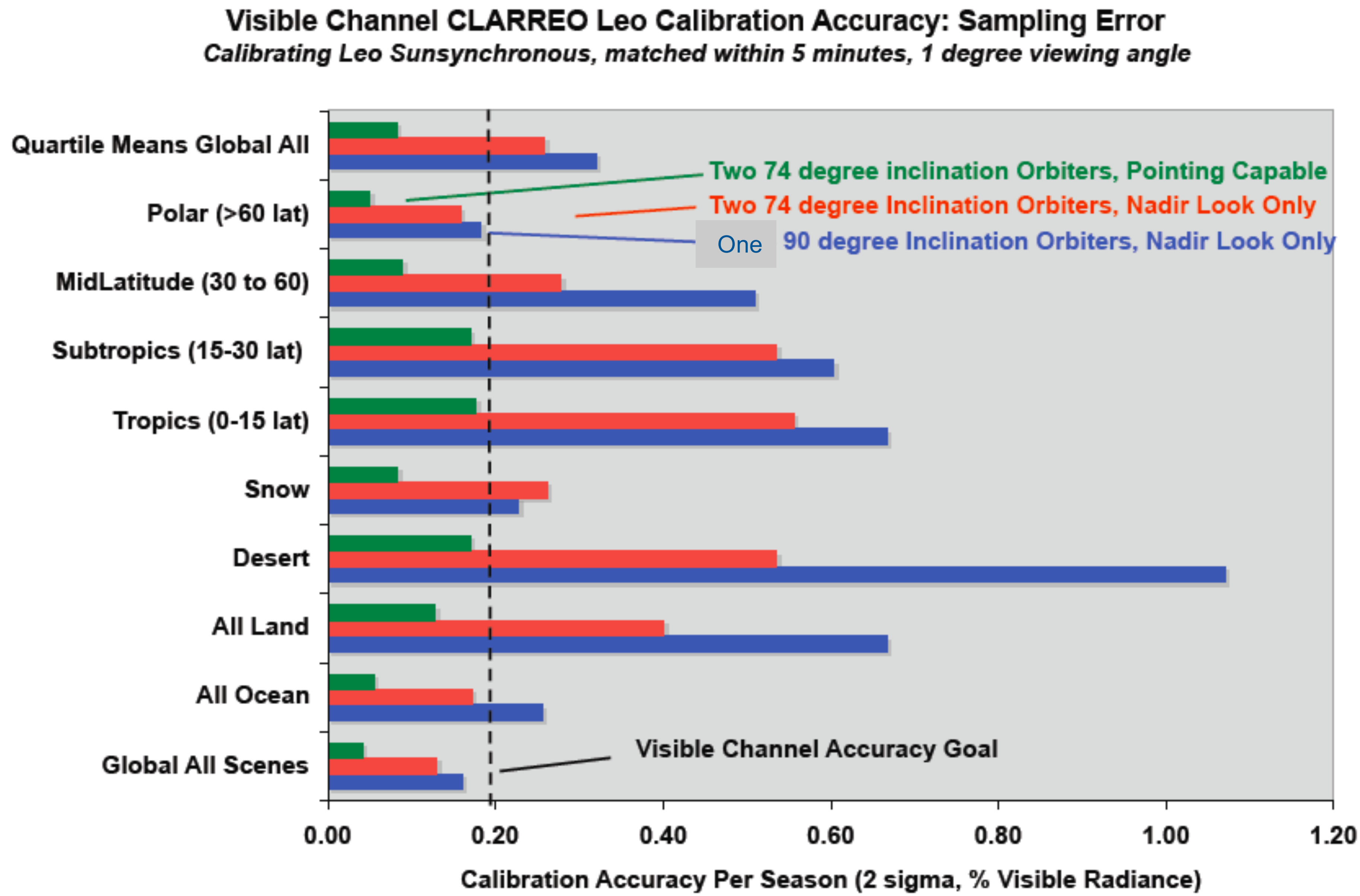
Conclusion: in 6 months can cross-calibrate across the entire Range of climate regimes: equator to pole, ocean to land. But is the sampling enough?



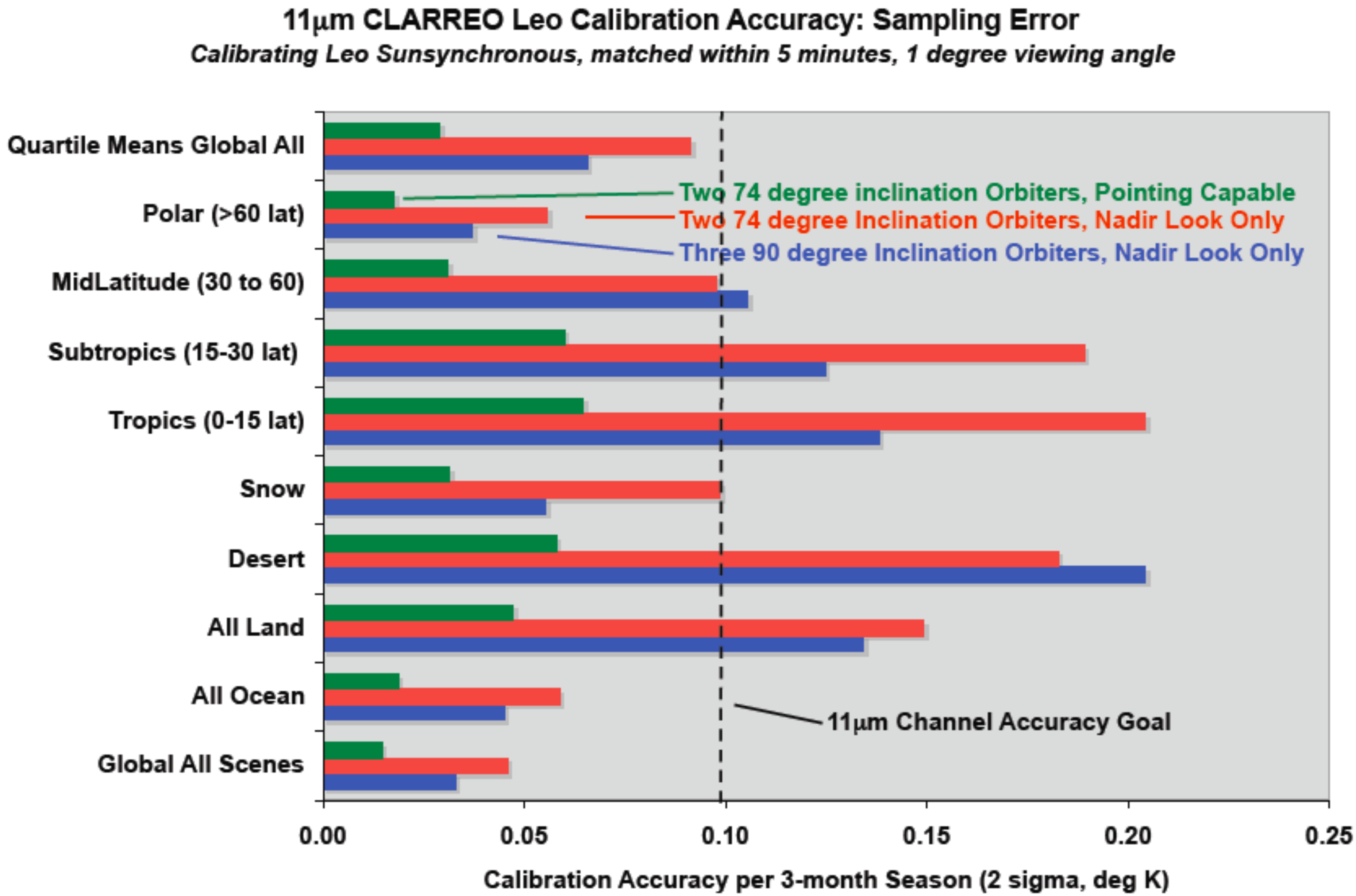
Conclusion: Solar Sampling Much Less: 1 satellite, day only



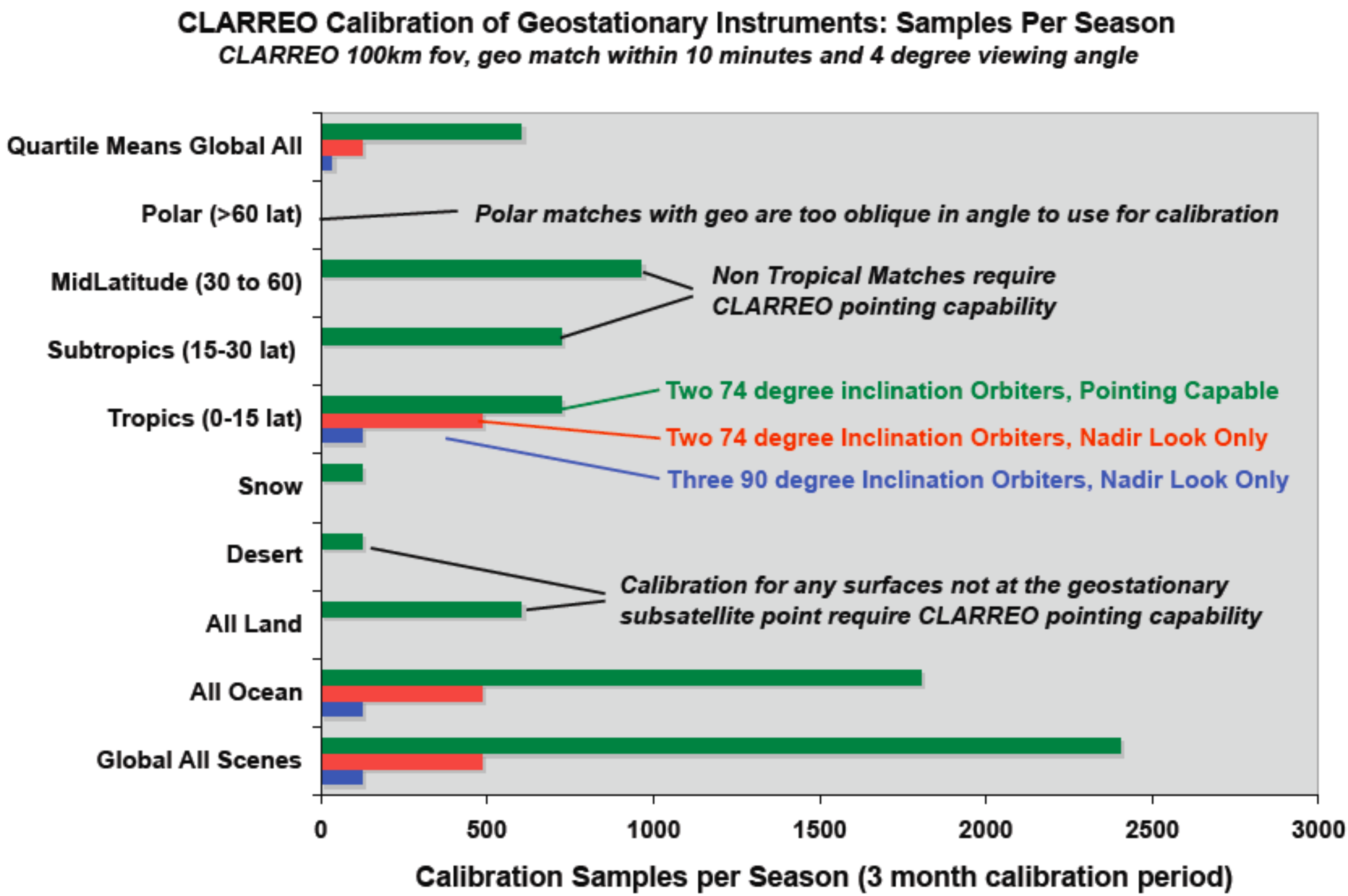
Conclusion: Poor Solar Sampling Doesn't Meet Accuracy Requirement



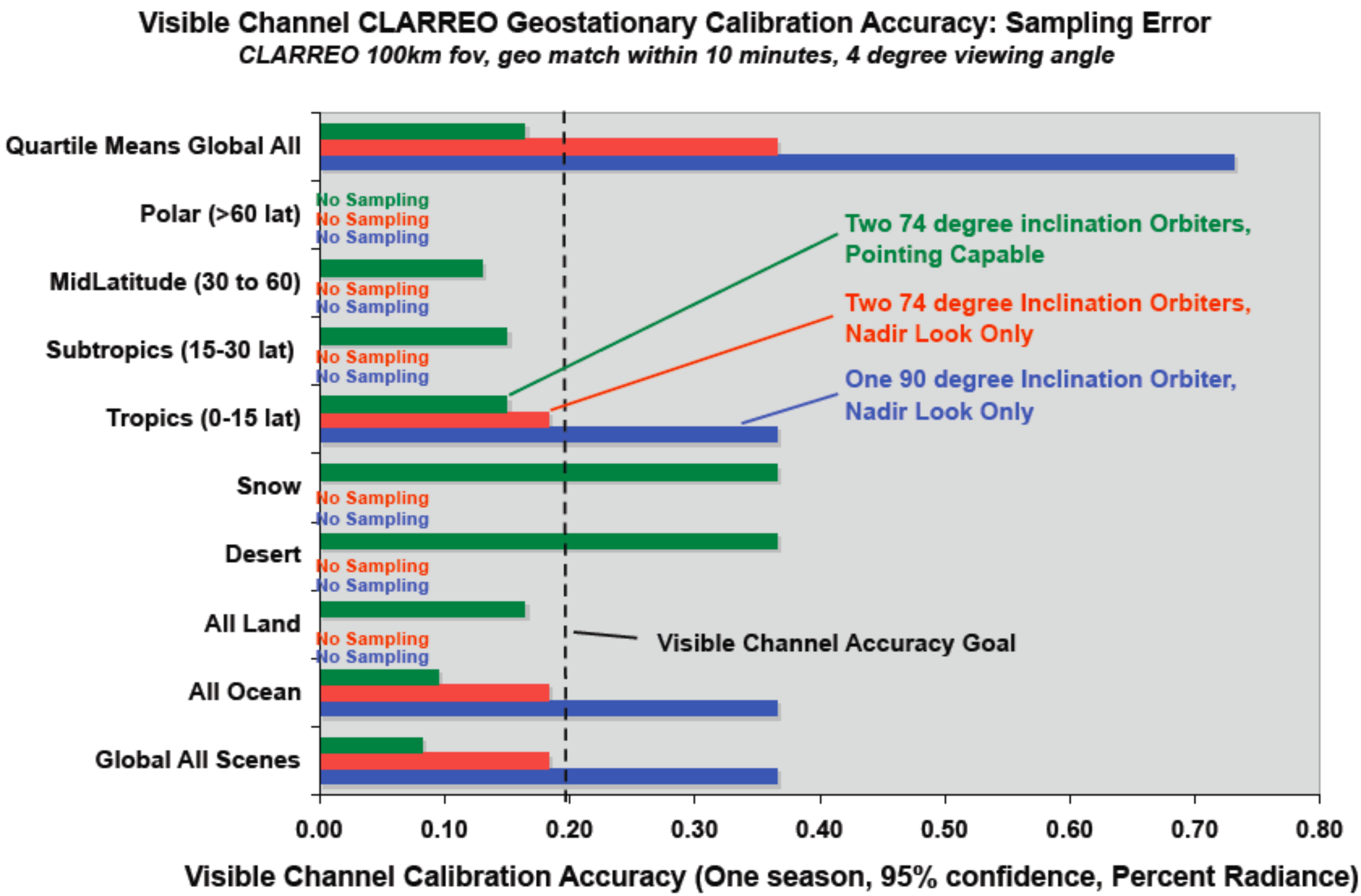
Conclusion: 2 Solar CLARREO sats and pointing (factor of 10 in samples Is key to meeting solar calibration goals.



Conclusion: 2 IR CLARREO sats and pointing (factor of 10 in samples Is sufficient to meet all infrared calibration goals.



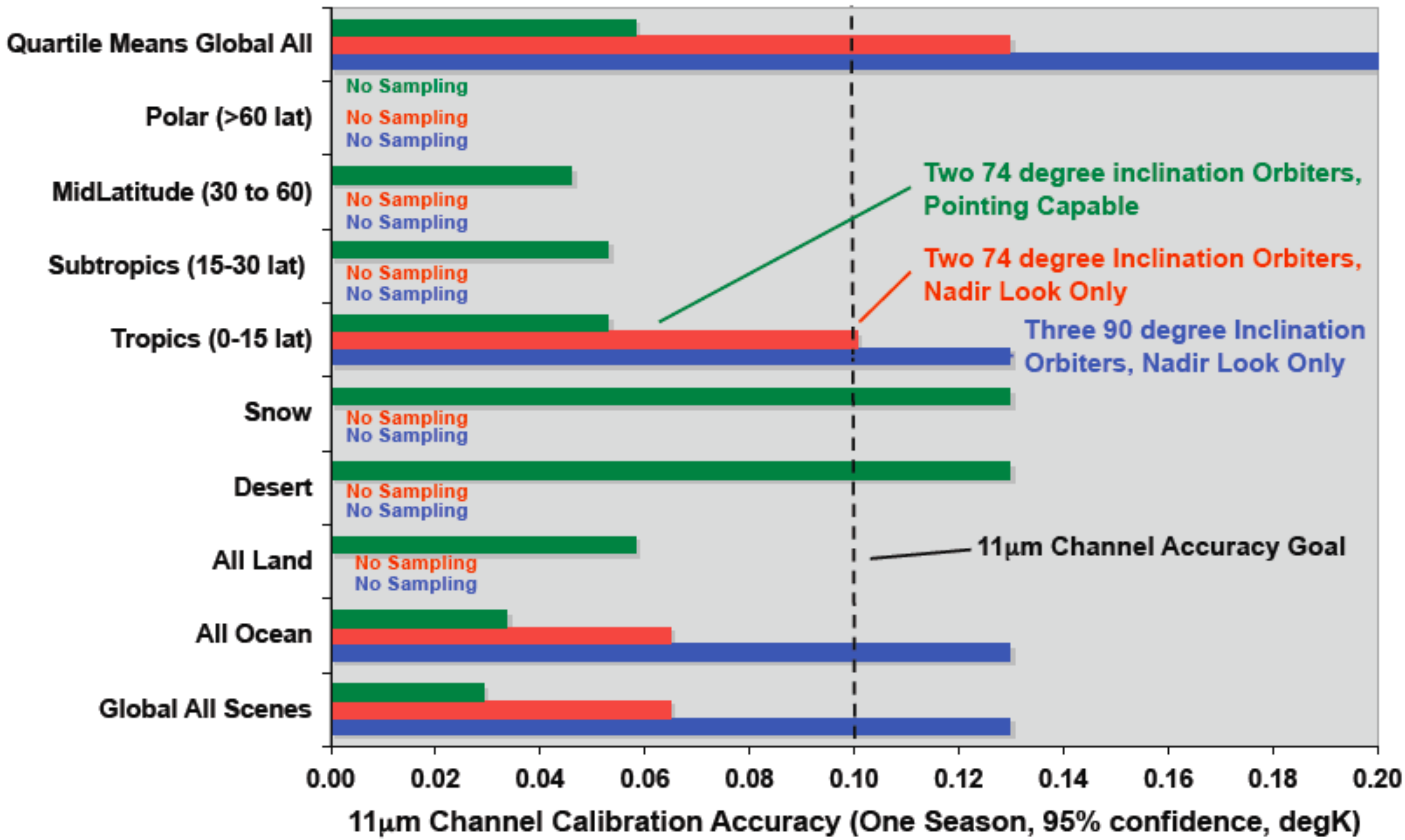
Conclusion: Pointing capability is critical to calibrate geostationary sensors at any position other than the sub-satellite equatorial point.



Conclusion: Pointing capability is critical to calibrate geostationary sensors for any solar reflectance channels

11µm Channel CLARREO Geostationary Calibration Accuracy: Sampling Error

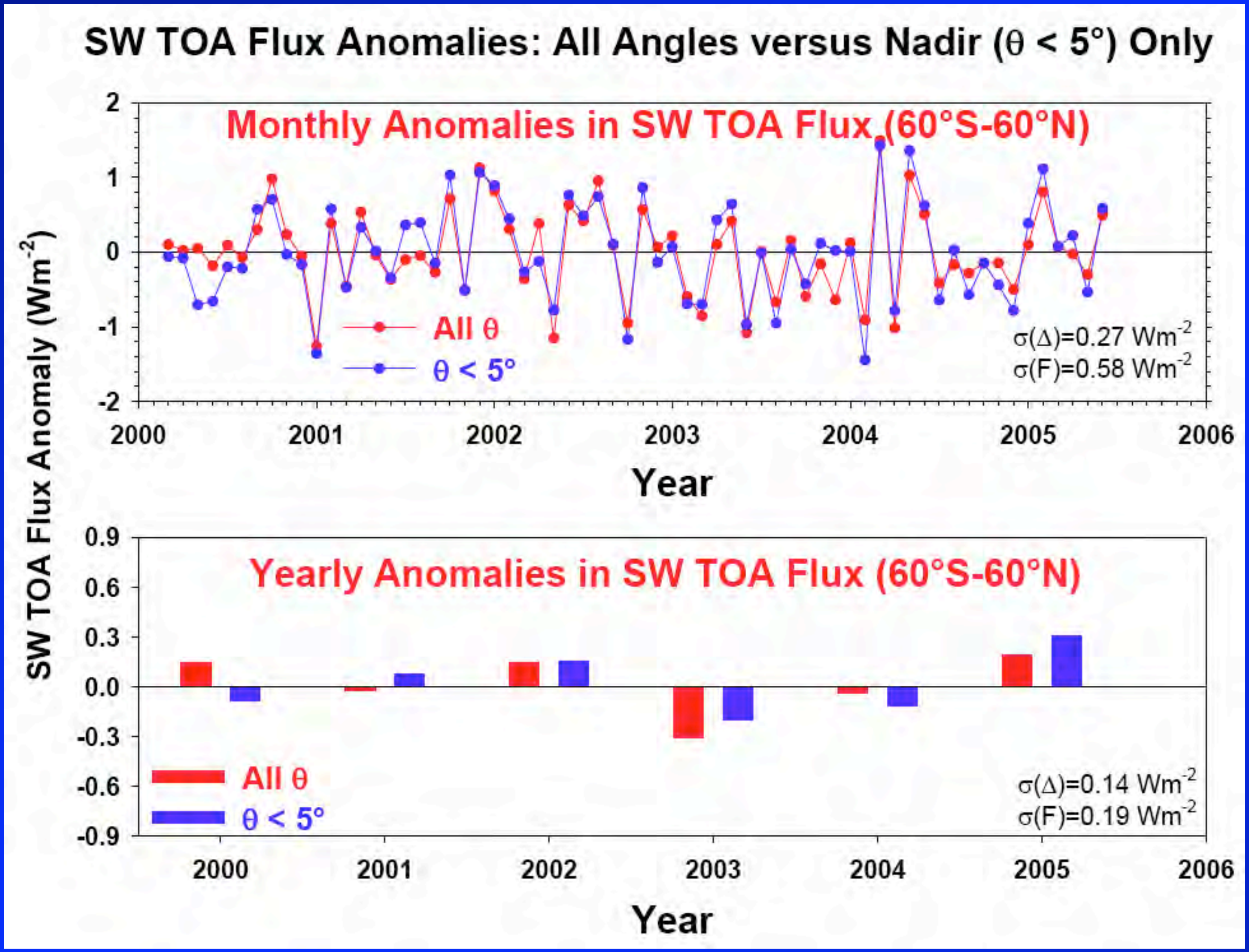
CLARREO 100km fov, geo match within 10 minutes, 4 degree viewing angle



Conclusion: Pointing capability is critical to calibrate geostationary infrared sensors for any conditions other than the geo subsatellite pt.

CLARREO Solar Benchmark Sampling Error

Nadir 100km vs Full Swath Scan



Monthly 60N to 60S
SW Nadir Only Noise:
0.27 Wm^{-2} (0.3%) 1σ
SW Climate Signal:
0.58 Wm^{-2} (0.6%) 1σ

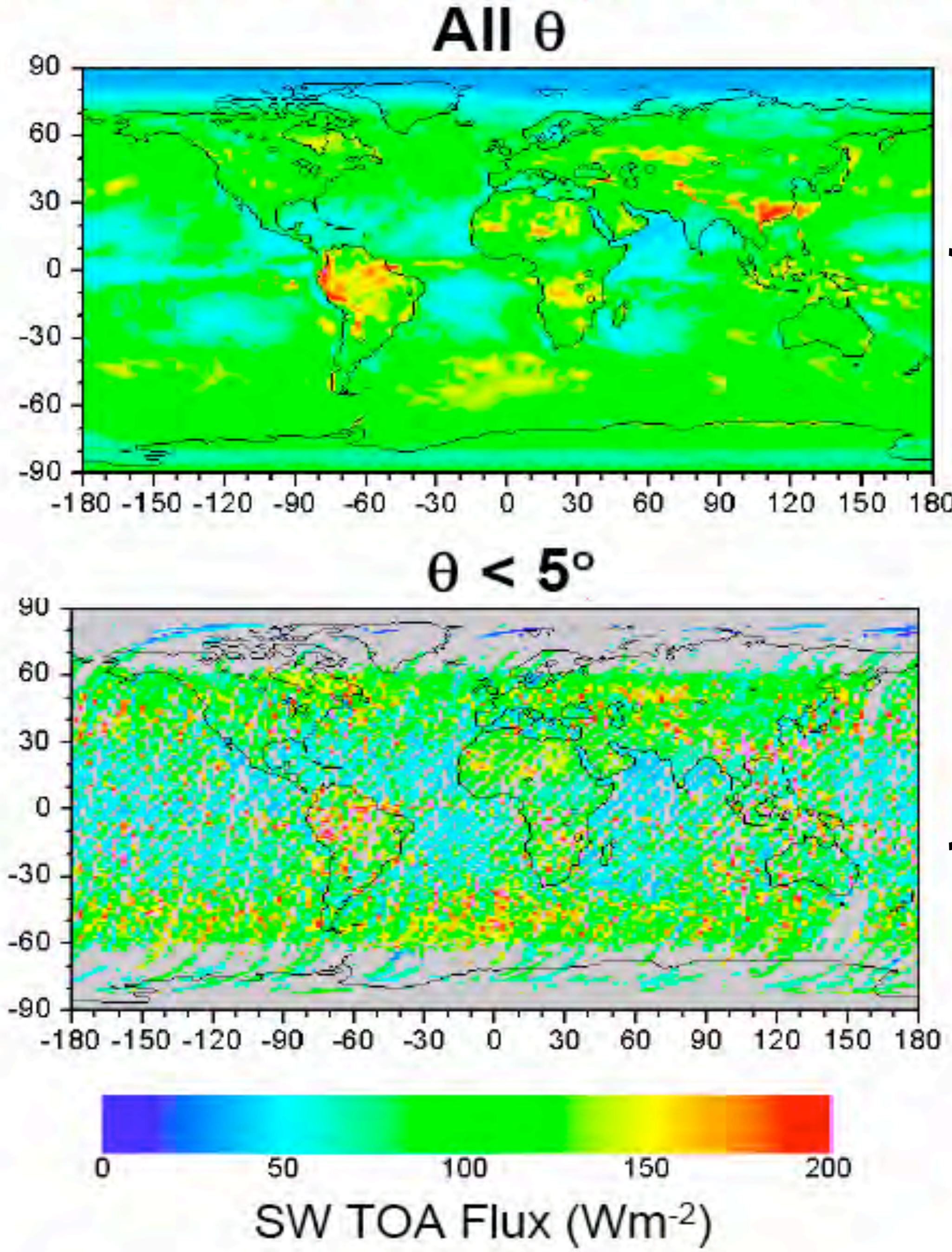
Annual 60N to 60S
SW Nadir Only Noise:
0.14 Wm^{-2} (0.15%) 1σ
SW Climate Signal:
0.19 Wm^{-2} (0.2%) 1σ

For global albedo: 1 CLARREO SW sat cannot achieve needed 5:1 S/N ratio. Annual mean sampling noise is as large as the signal. Instead focus CLARREO on calibration of full swath sensors, & providing spectral shape

Monthly Mean SW TOA Flux (CERES FM1; March 2000)

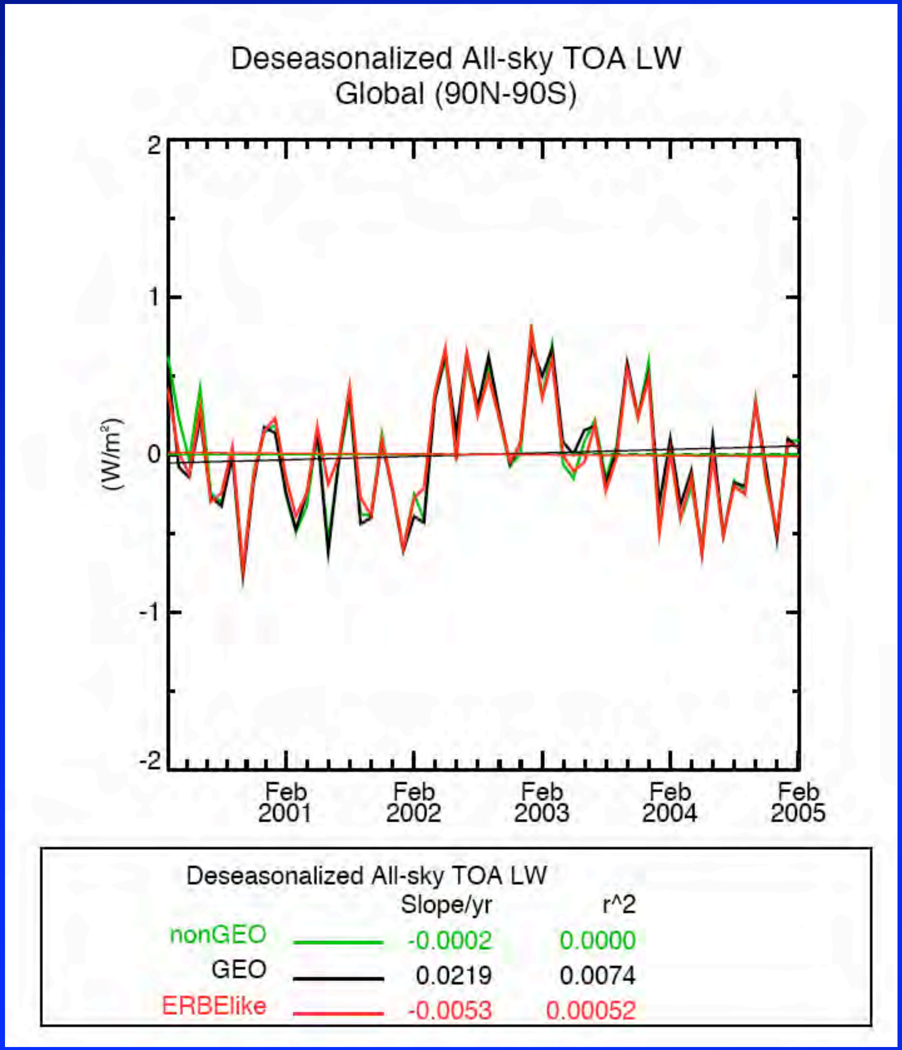
Full Swath Satellite Data (CERES Terra)

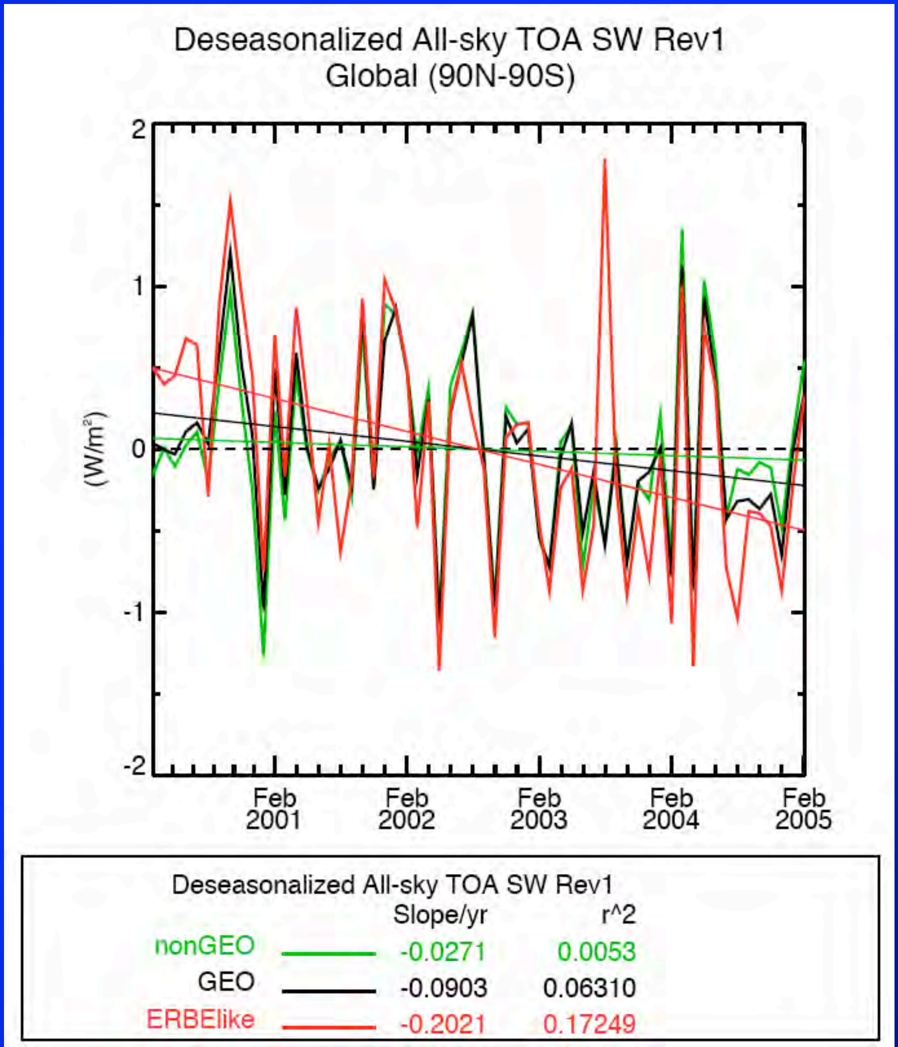
CLARREO Single Satellite Nadir 100km Field of View



Spatial sampling errors exceed magnitude of the mean field, Residual nadir only viewing angle biases also evident (e.g. subtropical ocean)

Diurnal Cycles: Once we have fixed sunsynch orbits (NPOESS, Terra): what is their decadal change?





Tropical and Global Mean Effect of Diurnal Cycle: Very Small

GEO is CERES + 3-hourly Geo Diurnal Cycle, nonGEO = CERES Terra Only

Conclusions and Next Steps

- **The CLARREO concept can calibrate the entire collection of LEO and GEO solar and infrared instruments**
  - This would be a critical contribution to a wide range of climate change observations from land to ocean to atmosphere and cryosphere.
  - Matching viewing angle between two LEO satellites, 40 seconds is available for every 100km of difference in orbit altitude: suggests 600km
  - 2 precessing orbits can under-fly all other satellites, and can ensure initial independence checks/overlap until prove absolute accuracy we think we can achieve. (90 or 74 degree inclination).
  - Field of view of 100km the sweet spot of minimizing angle/space match.
  - Spectral coverage to handle broadband calibration, spectral resolution to handle calibration and resolve spectral signatures.
  - A single CLARREO fixed pointing solar satellite can neither calibrate other instruments at 0.2%, nor can it sufficiently sample benchmark radiance/irradiance because of space/time/angle aliasing.
- **Solar reflected irradiance benchmark using one satellite with 100km swath is severely undersampled in space/time/angle.**
  - Need further analysis on ways to sample spectral dependence by scene type similarly to the way CERES handles missing angle sampling.
  - Need further analysis of use of spectral irradiance climate change metrics by climate models as diagnostics

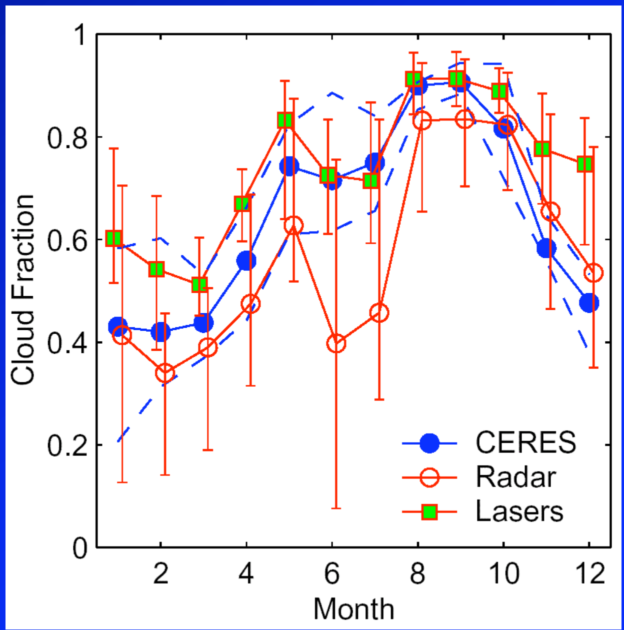
Conclusions and Next Steps

- Can we use CLARREO to calibrate IASI and CrIS to provide the IR benchmark records? Interferometers are well suited to intercalibration and spectral response function matching.
- CLARREO should push hard for absolute accuracy to SI standards. Need to demonstrate in orbit this is achieved: so first missions should have low risk of gaps even in CLARREO.
- CLARREO has the opportunity to raise the accuracy of many key climate data records: but only if orbit/fov/sampling are designed to achieve it.
- IR is likely to be much easier than solar.

Backup Slides

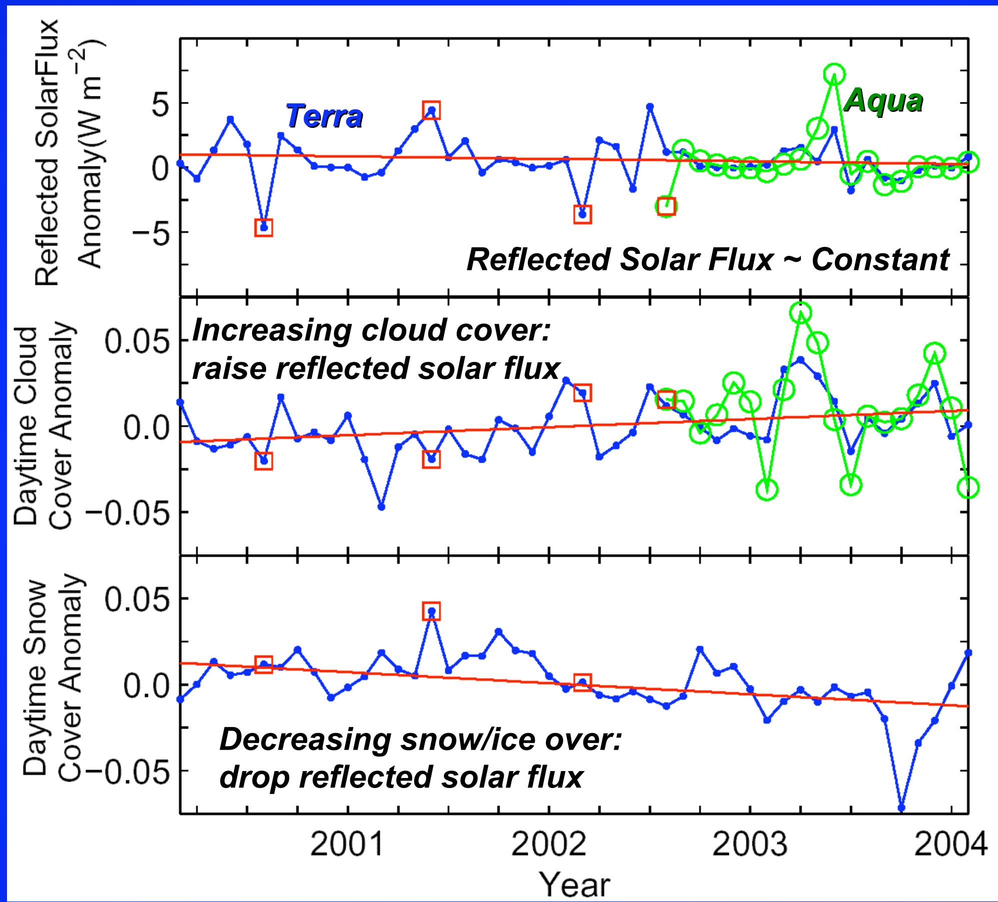
Arctic Warming: Are clouds offsetting much of the positive feedback of decreasing snow and ice?

Cloud Fraction at Barrow Alaska



CERES cloud analysis using MODIS data shows new polar cloud data compares well with surface lidar & radar from the DOE ARM site

Arctic (60N-90N) Trends from Terra & Aqua

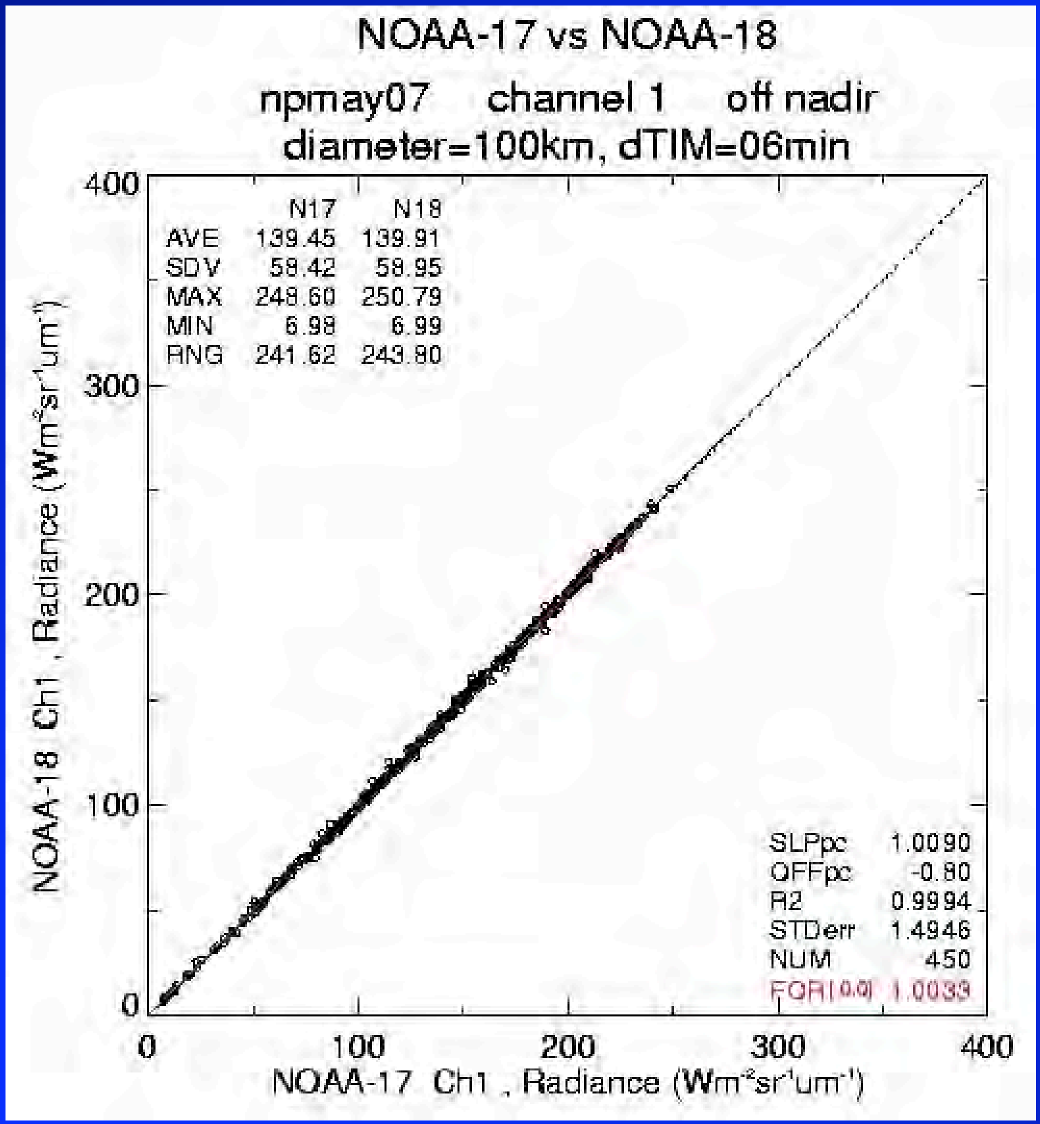


Currently, increasing Polar cloudiness is offsetting most of the positive climate feedback of decreasing Arctic snow and ice.

Will it continue?

Kato et al., GRL, 2006

NOAA 17 to 18 AVHRR Visible Channel Intercalibration



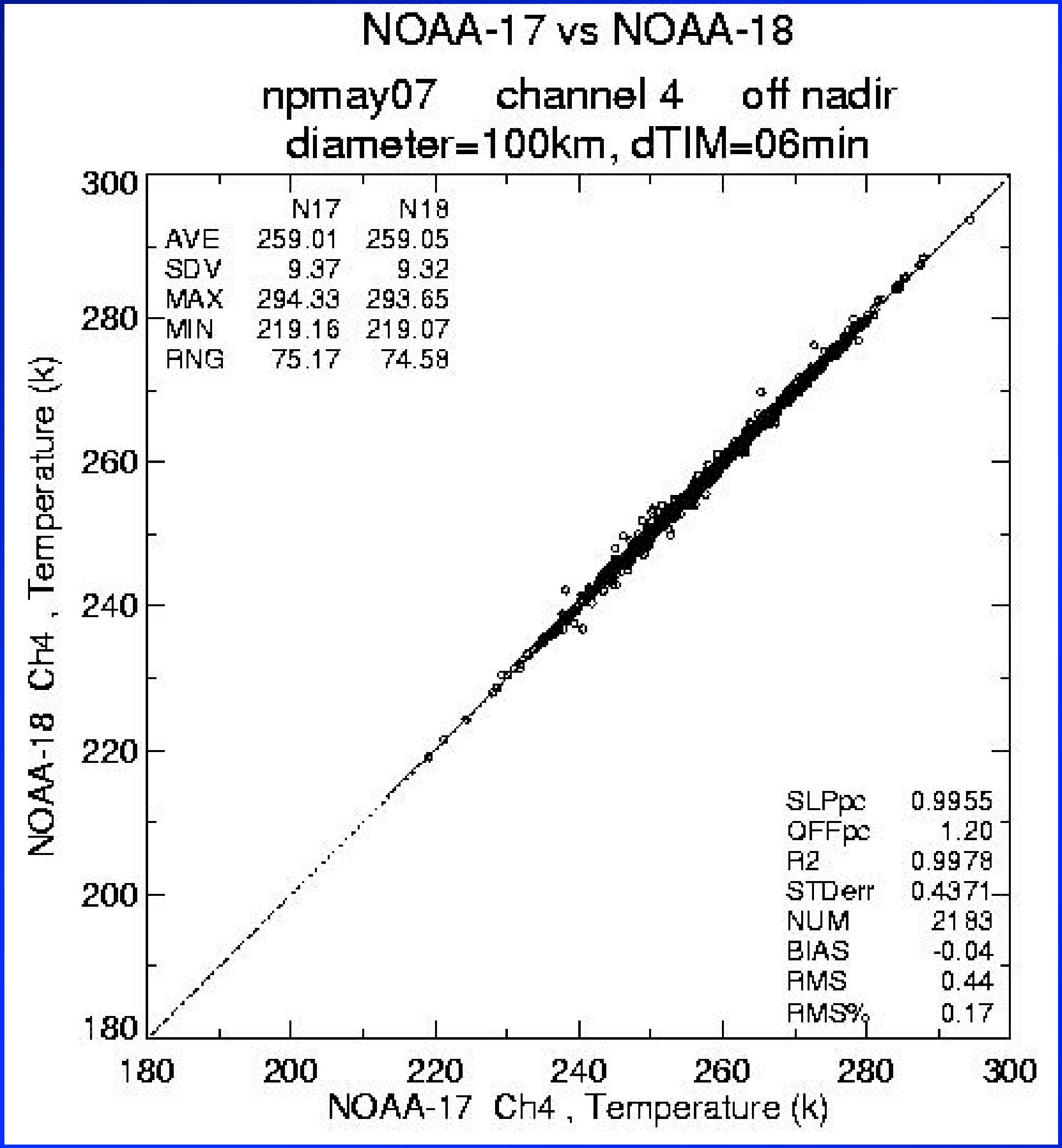
Spectral bandpasses agree, 100-km spatial match 1-degree angle match, 6-minute time match:

Sigma is 1.1% visible radiance For single 100km fov match.

Data shown is 3 months of matching data (Apr-May07)

Caveat: polar only

NOAA 17 to 18 AVHRR 11µm Window Channel Intercalibration



Spectral bandpasses agree, 100-km spatial match 1-degree angle match, 6-minute time match:

Sigma is 0.44K B. Temp. For single 100km fov match.

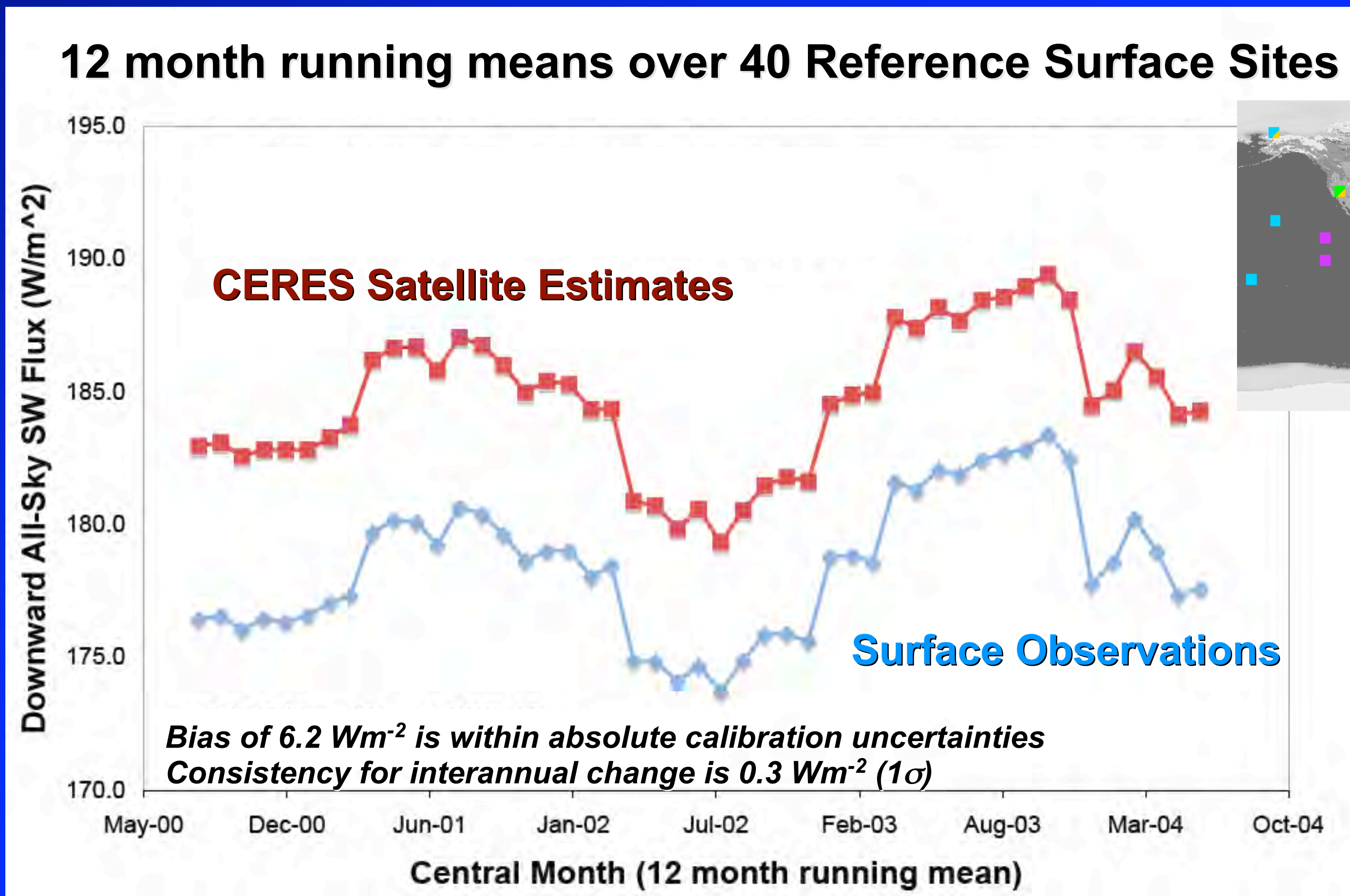
Data shown is 3 months of matching data (Apr-May07)

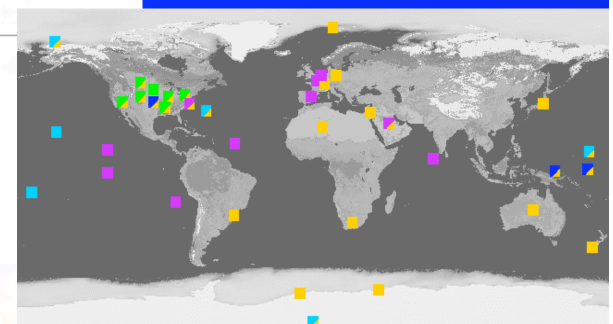
Caveat: polar only

CERES Surface Radiative Fluxes vs Surface Sites:

Interannual Anomalies Consistent at 0.2% or 0.3 Wm^{-2}

The first space-based global surface fluxes at climate change accuracy

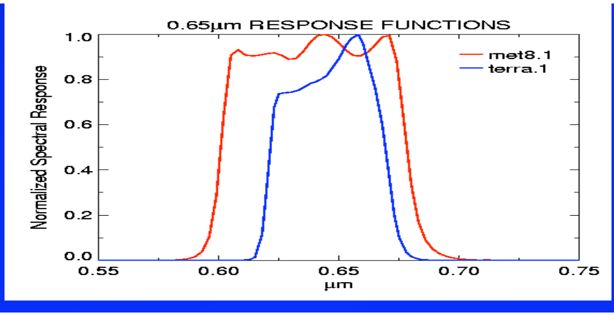


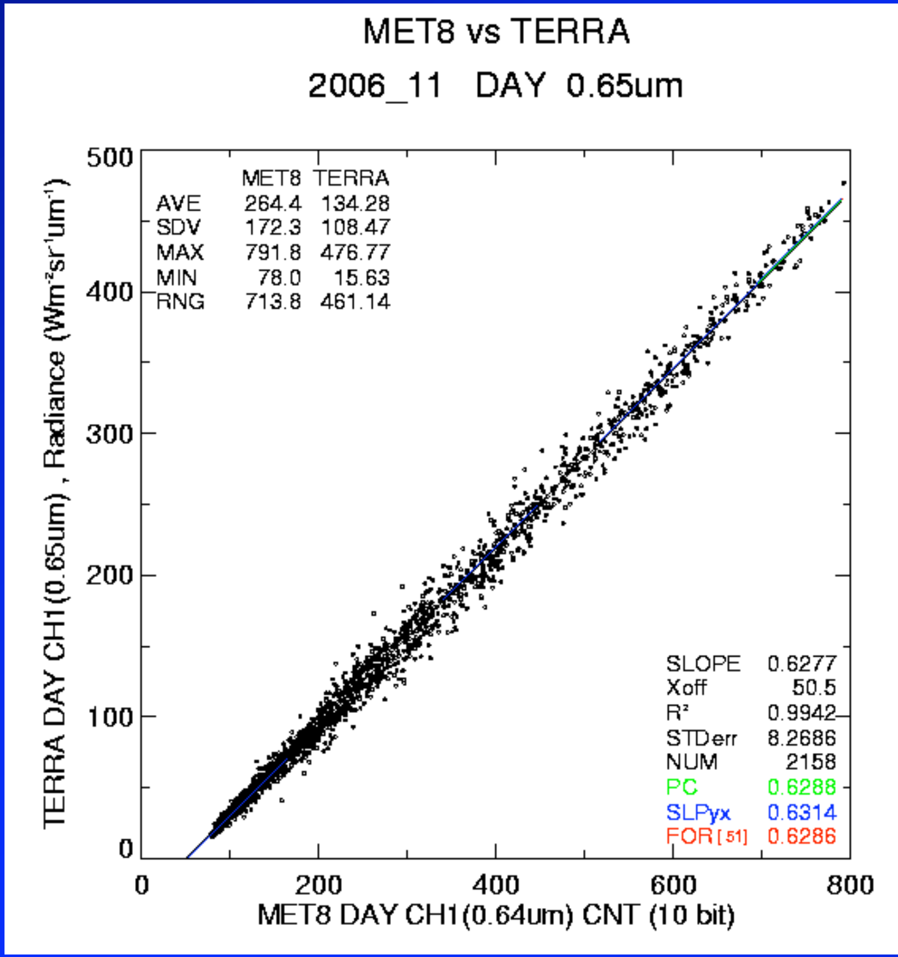


Sfc Site Map (ARM/BSRN/CMDL)

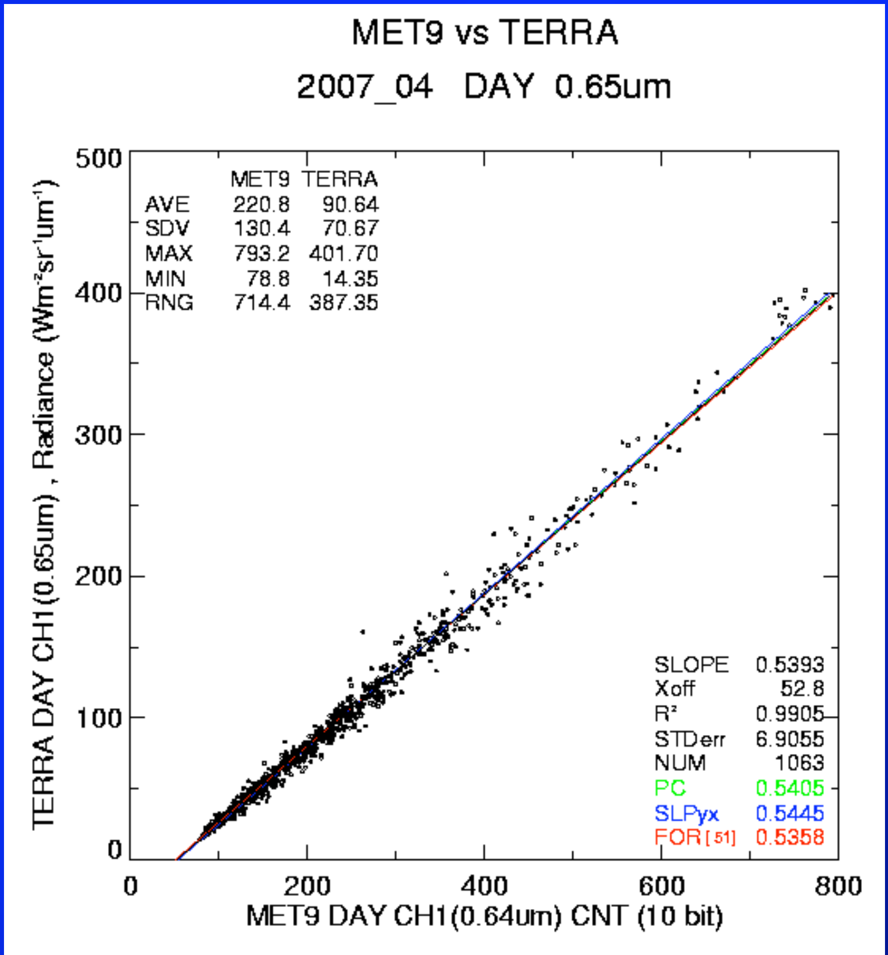
Global satellite sampling of radiation fields remains key: regional variability (climate noise) is very large: 10 times the global forcing of 0.6 Wm^{-2}/decade: even averaging 40 disperse surface sites (equator to pole, ocean islands, land and desert). GEWEX RFA

MET8/9 with Terra 0.63µm



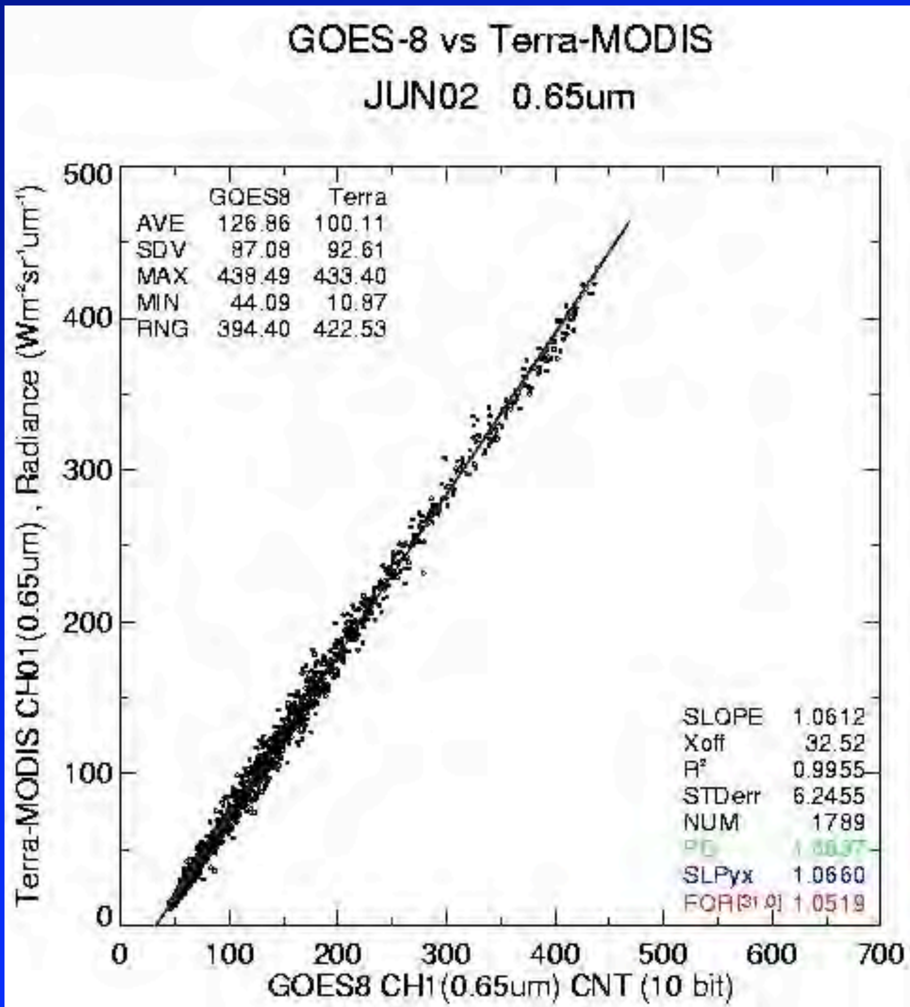


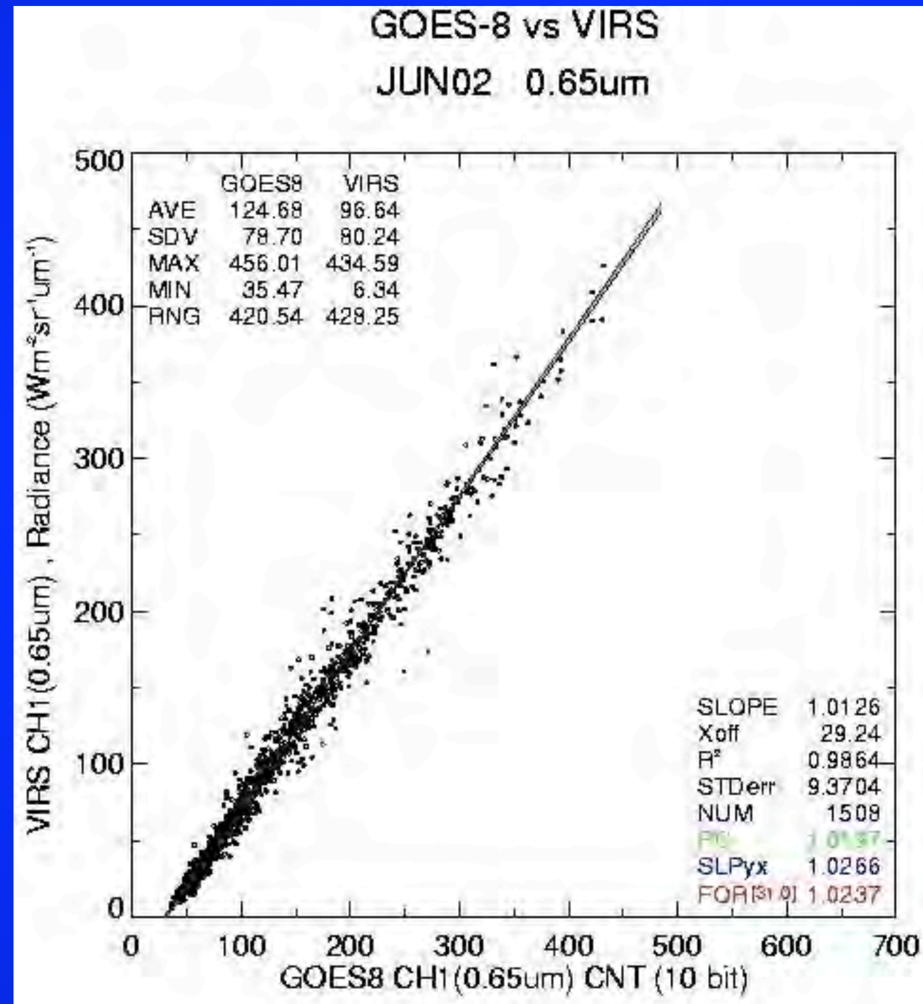
MET-8

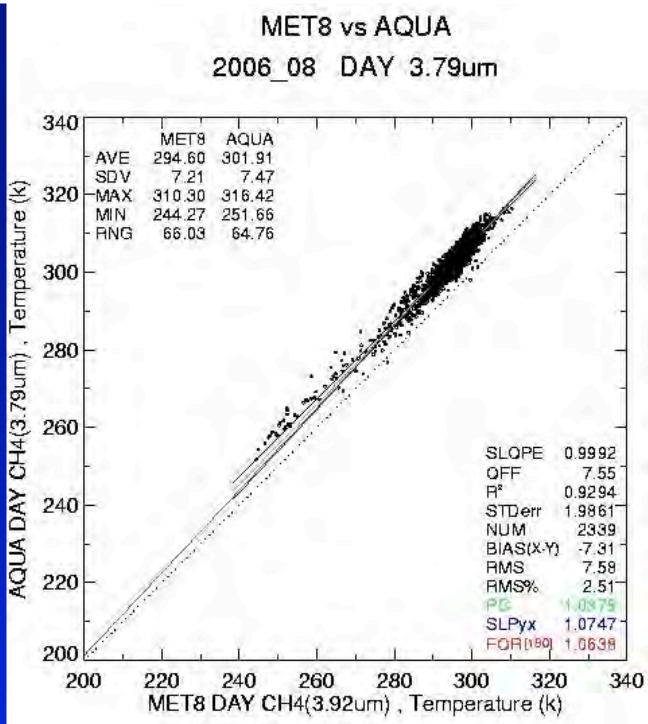


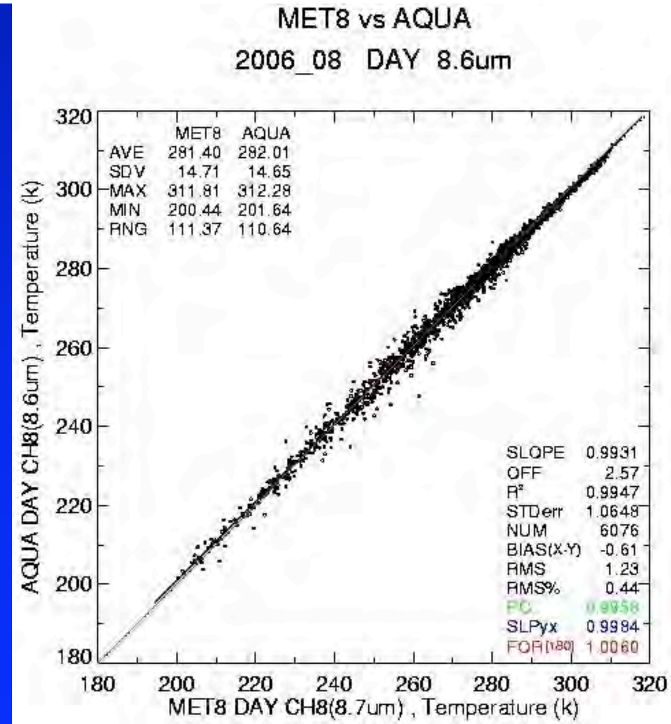
MET-9

Examples of LEO-to-GEO Normalizations



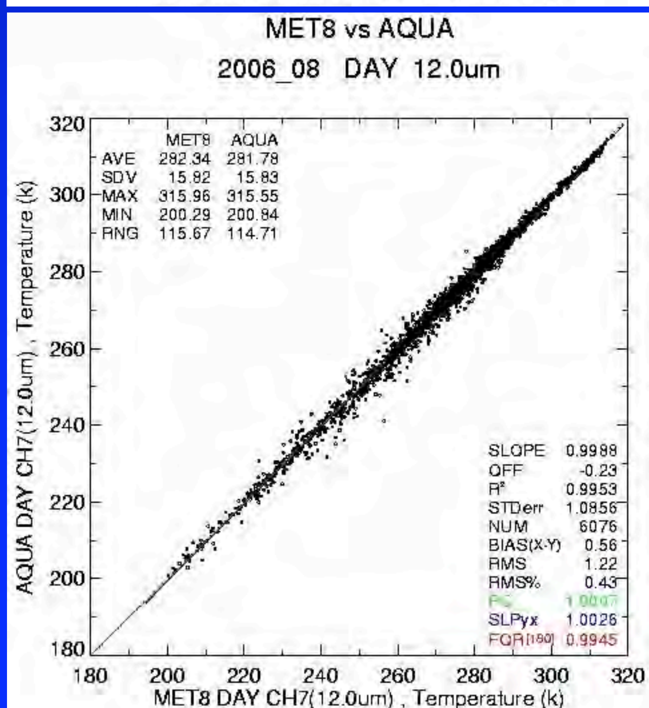


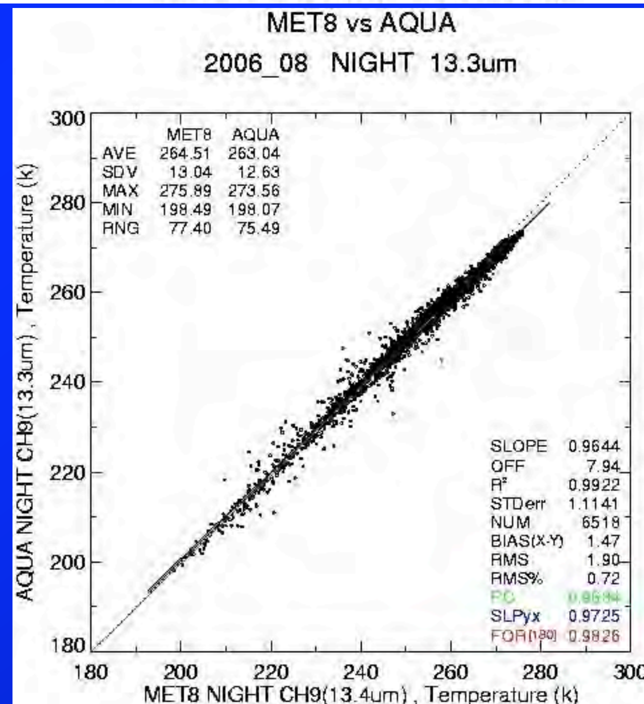




MET-8
vs
Aqua

Aug 2006





Archive Individual Pair Calibration SubPage

VIRS vs Terra-MODIS ***(version #4)***

- **Individual Monthly JPEG Plot**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000			1 2 3d 3n 4d 4n 5d 5n 4 5		1 2 3d 3n 4d 4n 5d 5n 4 5		1 2 3d 3n 4d 4n 5d 5n 4 5		1 2 3d 3n 4d 4n 5d 5n 4 5		1 2 3d 3n 4d 4n 5d 5n 4 5	
2001	1 2 3d 3n 4d 4n 5d 5n 4 5		1 2 3d 3n 4d 4n 5d 5n 4 5		1 2 3d 3n 4d 4n 5d 5n 4 5		1 2 3d 3n 4d 4n 5d 5n 4 5		1 2 3d 3n 4d 4n 5d 5n 4 5		1 2 3d 3n 4d 4n 5d 5n 4 5	
2002	1 2 3d 3n 4d 4n 5d 5n 4 5		1 2 3d 3n 4d 4n 5d 5n 4 5		1 2 3d 3n 4d 4n 5d 5n 4 5		1 2 3d 3n 4d 4n 5d 5n 4 5		1 2 3d 3n 4d 4n 5d 5n 4 5		1 2 3d 3n 4d 4n 5d 5n 4 5	
2003	1 2 3d 3n 4d 4n 5d 5n 4 5		1 2 3d 3n 4d 4n 5d 5n 4 5		1 2 3d 3n 4d 4n 5d 5n 4 5		1 2 3d 3n 4d 4n 5d 5n 4 5		1 2 3d 3n 4d 4n 5d 5n 4 5		1 2 3d 3n 4d 4n 5d 5n 4 5	
2004	1 2 3d 3n 4d 4n 5d 5n 4 5	1 2 3d 3n 4d 4n 5d 5n 4 5	1 2 3d 3n 4d 4n 5d 5n 4 5	1 2 3d 3n 4d 4n 5d 5n 4 5	1 2 3d 3n 4d 4n 5d 5n 4 5		1 2 3d 3n 4d 4n 5d 5n 4 5	1 2 3d 3n 4d 4n 5d 5n 4 5	1 2 3d 3n 4d 4n 5d 5n 4 5	1 2 3d 3n 4d 4n 5d 5n 4 5	1 2 3d 3n 4d 4n 5d 5n 4 5	
2005	1 2 3d 3n 4d 4n 5d 5n 4 5	1 2 3d 3n 4d 4n 5d 5n 4 5	1 2 3d 3n 4d 4n 5d 5n 4 5	1 2 3d 3n 4d 4n 5d 5n 4 5	1 2 3d 3n 4d 4n 5d 5n 4 5	1 2 3d 3n 4d 4n 5d 5n 4 5						

CHANNELS STATS MATCHING DATA ASCII
SPECTRAL RESPONSE FUNCTIONS: 0.65 1.6 3.7 11.0 12.0 Central wavelengths Corrk results

- **Timeline JPEG Plot**

	Slope	Yoffset	R2	STDerr	#	Bias	RMS	RMS%	Mave	Vave	SLPpc	SLPyx	SLPfor
0.65um	X	X	X	X	X	X	X	X	X	X	X	X	X
1.6um	X	X	X	X	X	X	X	X	X	X	X	X	X
3.7um	X	X	X	X	X	X	X	X	X	X	X	X	X
11um	X	X	X	X	X	X	X	X	X	X	X	X	X
12um	X	X	X	X	X	X	X	X	X	X	X	X	X

STATS ASCII

RETURN TO MAIN CALIBRATION PAGE

Example Intercalibration Calibration Page

Latest Calibrations Coefficients

GEO-satellite	MET-8	MET-5	FY2C	MTSAT	GOES-10 GOES-11	GOES-12
AVHRR-satellite	NOAA-15	NOAA-16	NOAA-17	NOAA-18		

GEO to GEO Cross-Calibrations calibration domains

FY2C 0.75um Night Examples problem good
FY2C 3.7um Night Examples problem good

	MET-8	MET-5	FY2C	MTSAT	GOES-10 GOES-11	GOES-12
MET-8	-	MET8/MET5	MET8/FY2C			MET8/GOES12
MET-5	MET5/MET8	-	MET5/FY2C			
FY2C	FY2C/MET8	FY2C/MET5	-	FY2C/MTSAT		
MTSAT			MTSAT/FY2C	-	MTSAT/GOES10 MTSAT/GOES11	
GOES-10 GOES-11				GOES10/MTSAT GOES11/MTSAT	-	GOES10/GOES12 GOES11/GOES12
GOES-12	GOES12/MET8			GOES12/GOES10	GOES12/GOES11	-

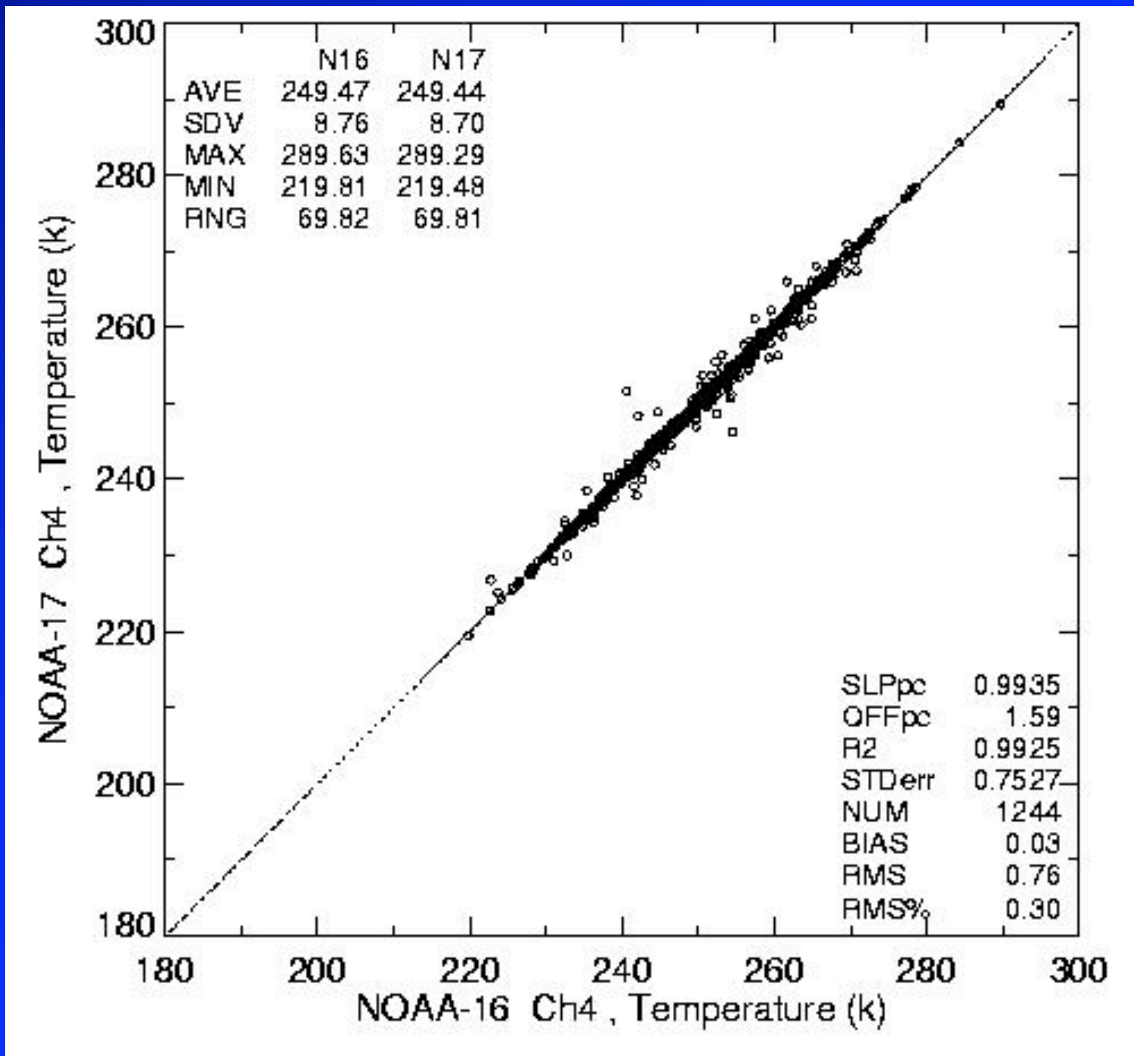
GEO to LEO Calibrations calibration domains

	MET-8	MET-5	FY2C	MTSAT	GOES-10 GOES-11	GOES-12
Terra-MODIS	Terra/MET8	Terra/MET5	Terra/FY2C	Terra/MTSAT	Terra/GOES10 Terra/GOES11	Terra/GOES12
Aqua-MODIS	Aqua/MET8	Aqua/MET5	Aqua/FY2C	Aqua/MTSAT	Aqua/GOES10 Aqua/GOES11	Aqua/GOES12
VIRS	VIRS/MET8	VIRS/MET5	VIRS/FY2C	VIRS/MTSAT	VIRS/GOES10 VIRS/GOES11	VIRS/GOES12
NOAA16-AVHRR	NOAA16/MET8					NOAA16/GOES12
NOAA17-AVHRR	NOAA17/MET8					NOAA17/GOES12
NOAA18-AVHRR	NOAA18/MET8					NOAA18/GOES12

AVHRR NOAA-16 to NOAA-17 Calibration: 11μm

50km region, dT<5min, dAngle<1deg

"same" spectral response function



0.65% channel gain difference (slope)

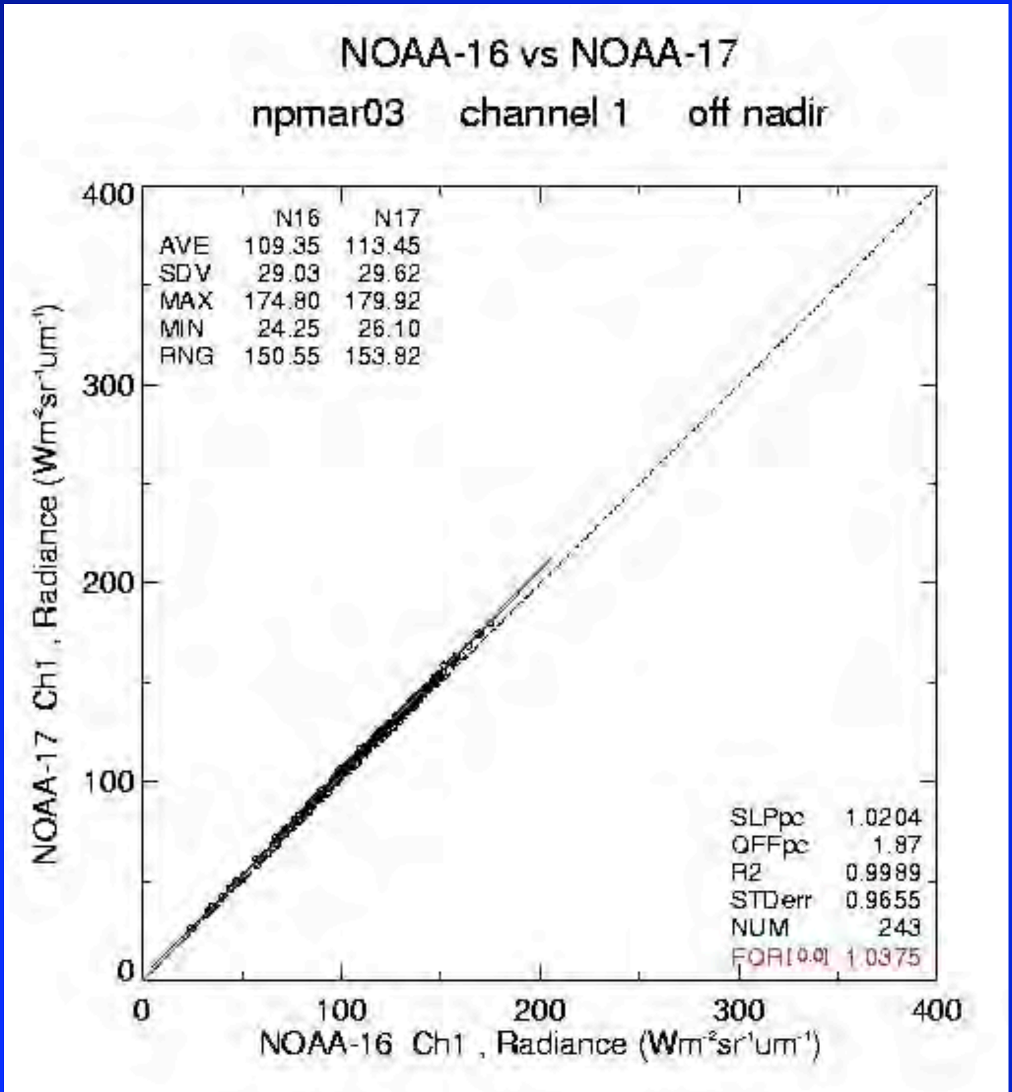
0.6% zero level difference (offset)

0.3% matching noise
0.8K matching noise
(both 1σ)

Doelling, Minnis, Nguyen
GSICS meeting, June 07

AVHRR NOAA-16 to NOAA-17 Calibration: 0.65μm

50km region, dT<5min, dAngle<1deg
"same" spectral response function



2.0% channel gain difference (slope)

1.7% zero level difference (offset)

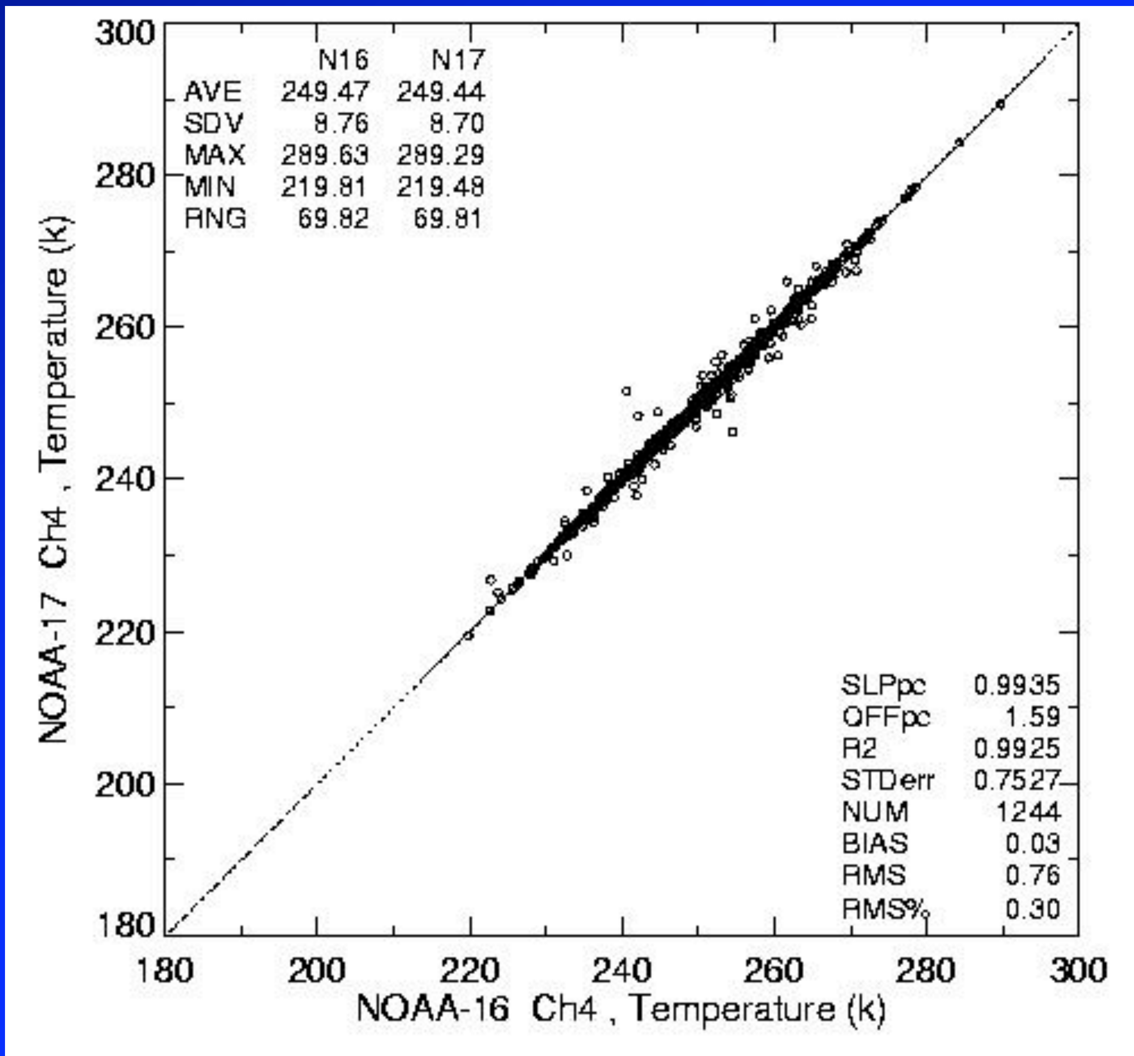
0.9% matching noise (1σ)

Doelling, Minnis, Nguyen
GSICS meeting, June 07

AVHRR NOAA-16 to NOAA-17 Calibration

50km region, dT<5min, dAngle<1deg

Spectral response function very similar



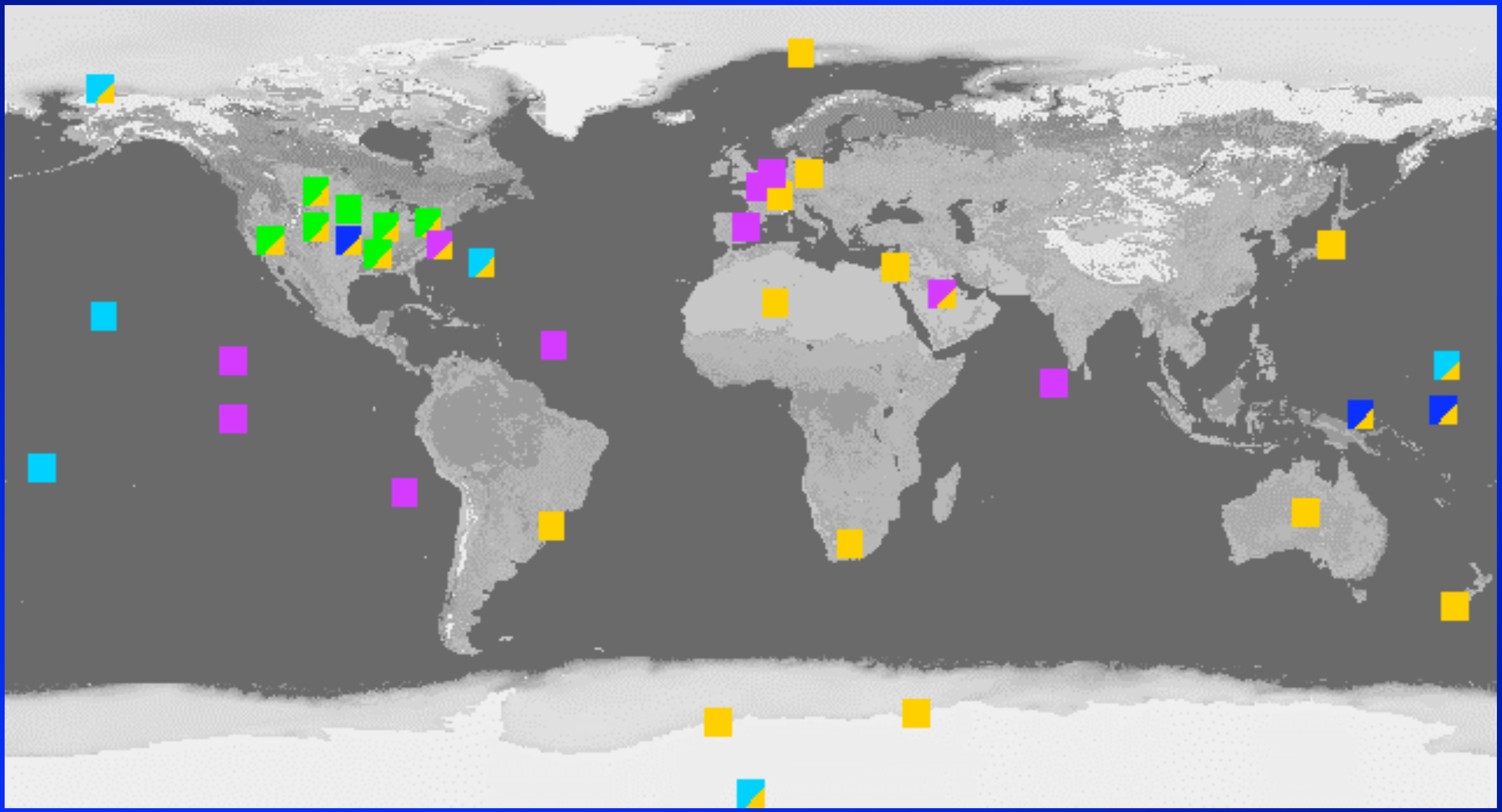
0.65% channel gain difference (slope)

0.6% zero level difference (offset)

0.3% matching noise
0.8K matching noise
(both 1σ)

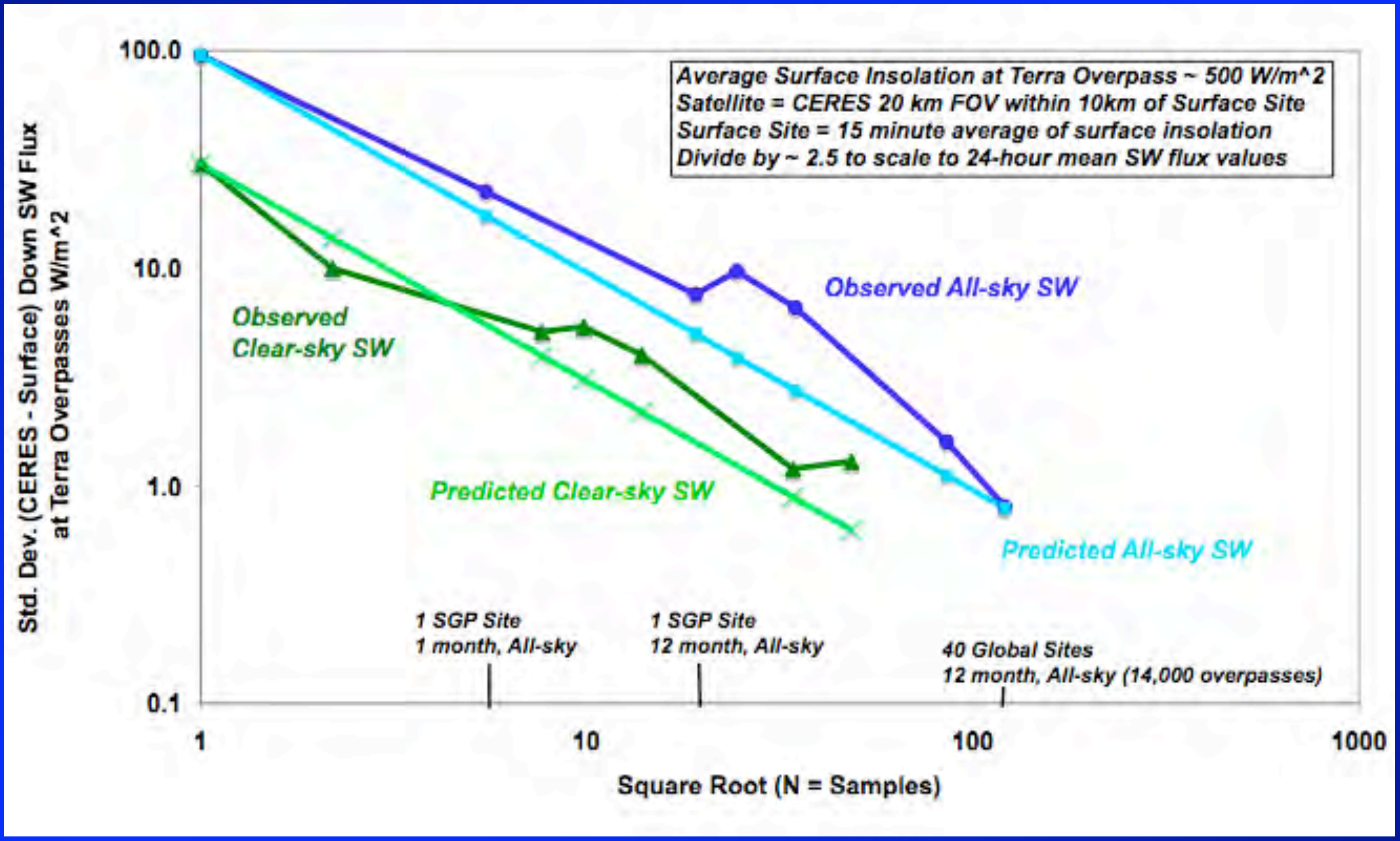
Doelling, Minnis, Nguyen
GSICS meeting, June 07

ARM/BSRN/CMDL/Surfrad Surface Radiation Sites



Surface SW Flux Validation Noise

Spatial mismatch of surface point to satellite area



Surface Downward Flux Errors: 20 - 40 Surface Sites

	Global Interannual Cld Rad Fcing Variability	SYN/AVG (est) Month, 1-deg Bias, Clr/All (1 σ)	SRBAVG Month, 1-deg Bias All (1σ)	CRS 20km fov Instantaneous 1 σ, Clr/All Sky (S_o = 900)
Dominant Error Sources	TBD	Aerosol, Tair, Polar sfc/cld Site Inhom.	Aerosol, Tair, Param. Site Inhom.	Angle Samp, Water Vapor Aerosol, Tair
Surface Down SW Flux	0.5 Wm^{-2} (40 sites)	0 / +5 Wm^{-2} (σ = 6)	3 Wm^{-2} (σ = 20)	23 / 20 Wm^{-2}
Surface Down LW Flux	1.0 Wm^{-2} (40 Sites)	-7 / -6 Wm^{-2} (σ = 8)	< 1 Wm^{-2} (σ = 10)	12 / 17 Wm^{-2}
Surface Down Total Net Flux	1.1 Wm^{-2} (40 Sites)	-7 / -1 Wm^{-2} (σ = 9)	4 Wm^{-2} (σ = 22)	26 / 26 Wm^{-2}
Science	TBD	< 5-10 Wm^{-2}	< 5-10 Wm^{-2}	< 25 Wm^{-2}

Global Net Flux Balance Error Budget

(out of 1365/ 4 = 341.25 Wm^{-2} = SW + LW)

Error Source (white = heating)	SW	LW	Net
Solar Constant (1361 vs 1365)	+ 1.0	0.0	+ 1.0
Non-Spherical Earth Insolation	+ 0.4	0.0	+ 0.4
Absolute Calibration (95% conf)	2.0	2.0	4.0
Spectral Correction	0.5	0.3	0.8
Spatial Sampling	< 0.1	< 0.1	< 0.1
Angle Sampling (ADMs)	+ 0.2	- 0.1	+ 0.1
Time Sampling (diurnal)	< 0.2	< 0.2	< 0.2
Reference Altitude (20km)	0.1	0.2	0.3
Twilight SW Flux (= 0.25 Wm^{-2})	< 0.1	0.0	< 0.1
Near Terminator SW Flux (85-90)	+ 0.5	0.0	+ 0.5
3-D Cloud τ_{vis} bias on $\alpha(\Theta_o)$	+ 0.5	0.0	+ 0.5
Ocean Heat Storage			+ 0.4 - 1.0
Expected Global Net Range:			-1.0 to + 7.2
CERES SRBAVG Ed2D Rev 1 Global Net			+ 6.4

- ***Absolute Accuracy in global net flux requires much more than absolute calibration, although this currently remains the largest error source.***

TOA Flux Errors

	Global Interannual Cld Rad Fcing Trend/decade	Zonal Eqtr - Pole Gradient Monthly	1 deg region Monthly (1 σ)	20km fov Instantaneous (1 σ) (S_o = 1000)
Dominant Error Sources	Calibration Stability	Angle Sampling Twilight	Calibration Time Sampling	Angle Sampling
TOA SW Flux	0.3 Wm^{-2} Terra Rev1	3.5 Wm^{-2}	3.0 Wm^{-2}	10 Wm^{-2}
TOA LW Flux	0.5 Wm^{-2} Terra Rev1	2.0 Wm^{-2}	1.5 Wm^{-2}	5 Wm^{-2}
TOA Net Flux	0.6 Wm^{-2} Terra Rev1	4.0 Wm^{-2}	3.5 Wm^{-2}	11 Wm^{-2}
Science Rqmt	0.15 Wm^{-2} 25% feedback	1 - 3 Wm^{-2}	2 - 5 Wm^{-2}	10 Wm^{-2}

What are the Calibration Requirements

- NASA/NOAA/NIST/NPOESS Satellite Climate Calibration Nov. 2002 Workshop (Ohring et al., BAMS Sept 2005)
- Follow up Global Climate Observing System (GCOS) international report.
- Follow up ASIC^3 workshop (May 2006)
- Metrics: global climate forcing, response, feedback
  - 5:1 signal to noise ratio for global decadal change
  - Calibration Specs: absolute accuracy and stability/decade.
  - Typical infrared: absolute 0.1 - 0.5K, stability 0.04 - 0.2K
  - Typical solar reflected: absolute 1 - 3%, stability 0.1 to 0.5%
  - Use of stability is very vulnerable to data gaps
  - If allow data gaps: must achieve stability level requirements for absolute accuracy: 0.04K for IR, 0.1% for solar reflected: these can be considered 1sigma, so 95% confidence is 0.08K in IR and 0.2% in solar reflected.
  - As error increases, time to detect trends increases

Confidence in Trend Detection:
years to detect vs noise σ_N

Estimation of deseasonalized trend detection time:

$$n^* \approx \left[\frac{3.3\sigma_\varepsilon}{|\omega_0|(1-\phi)}\right]^{2/3} = \left[\frac{3.3\sigma_N}{|\omega_0|}\sqrt{\frac{1+\phi}{1-\phi}}\right]^{2/3}$$

where: (Eqn. 3, Weatherhead et al., JGR, 1998.)

σ_N = noise (climate "noise" plus observation uncertainty)
ω_0 = magnitude of trend sought (per year)
n* **= number of years for trend detection**
(We are 90% sure that the specified trend will be detected with 95% confidence by this time.)

Rules of thumb from this equation:

a) 3 times larger noise leads to 2 times longer detection time (~ $\sigma^{2/3}$)
b) 3 times larger trend leads to 1/2 the detection time (~ $\omega_o^{-2/3}$)
c) If noise and trend increase by the same ratio: same detection time.

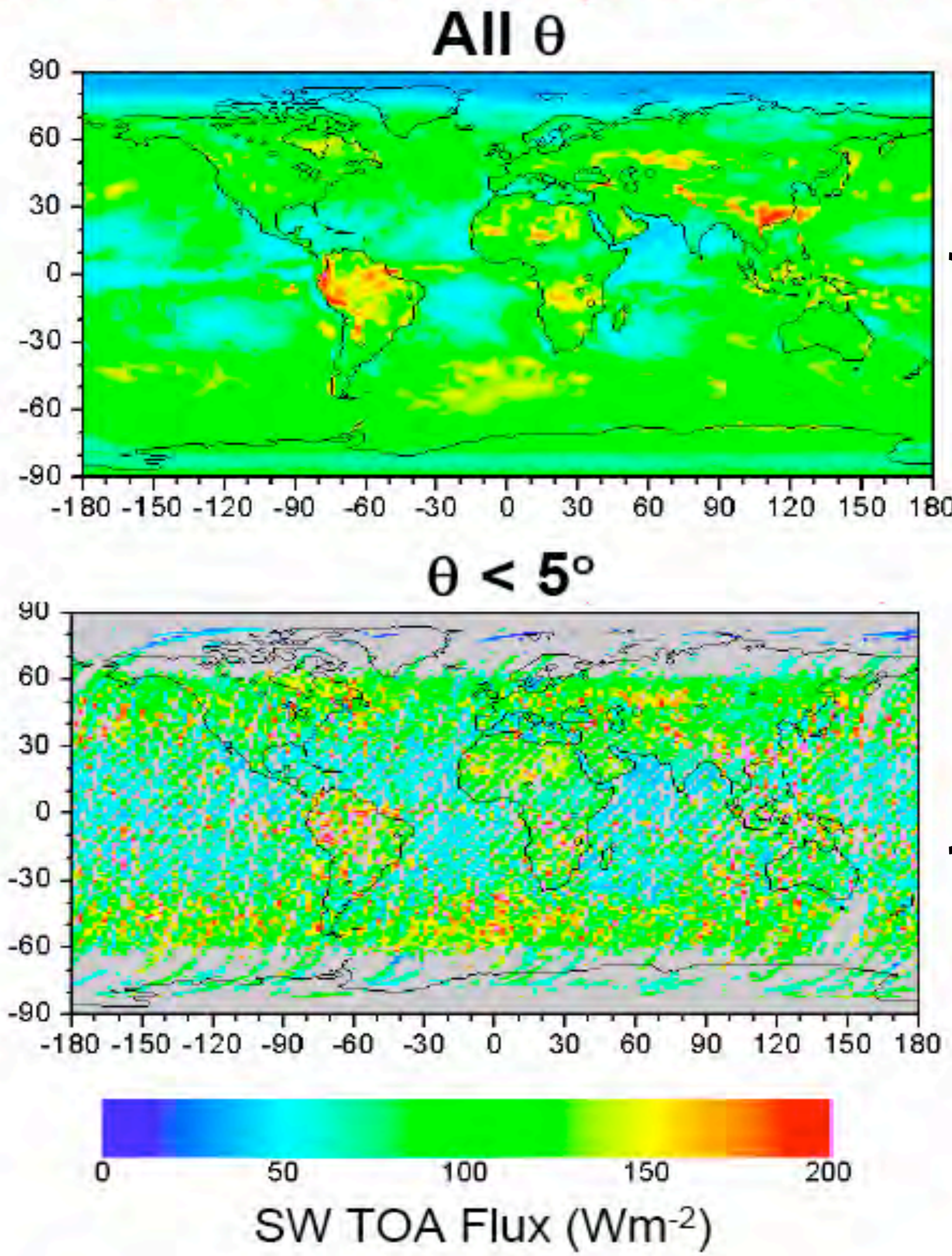
TOA Flux Decadal Variations

- Years N to detect trend ω with noise σ (natural variability plus observation uncertainty) scales as:

  $$N \sim (\sigma/\omega)^{2/3} \quad \text{(B. Weatherhead, 1998)}$$

  - *3 times larger noise leads to 2 times longer detection time (~ $\sigma^{2/3}$)*
  - *3 times larger trend leads to 1/2 the detection time (~ $\omega_o^{-2/3}$)*
  - *If noise and trend increase by the same ratio: same detection time.*
- At large time/space scales (e.g. global annual) climate variability "noise" is minimum, but issues with instrument calibration and consistent space/time sampling are significant. At smaller time/space scales climate variability is much larger, but so might be signals. We currently cannot evaluate an advantage at regional/zonal/global scales. Need further analysis to quantify σ and N versus time/space. Use climate model ensembles for ω hypothesis to "test"?
- Need improved studies of climate change metrics and their ability to constrain prediction accuracy using large ensembles of climate models with varying climate physics, sensitivity, climate change.

Monthly Mean SW TOA Flux (CERES FM1; March 2000)



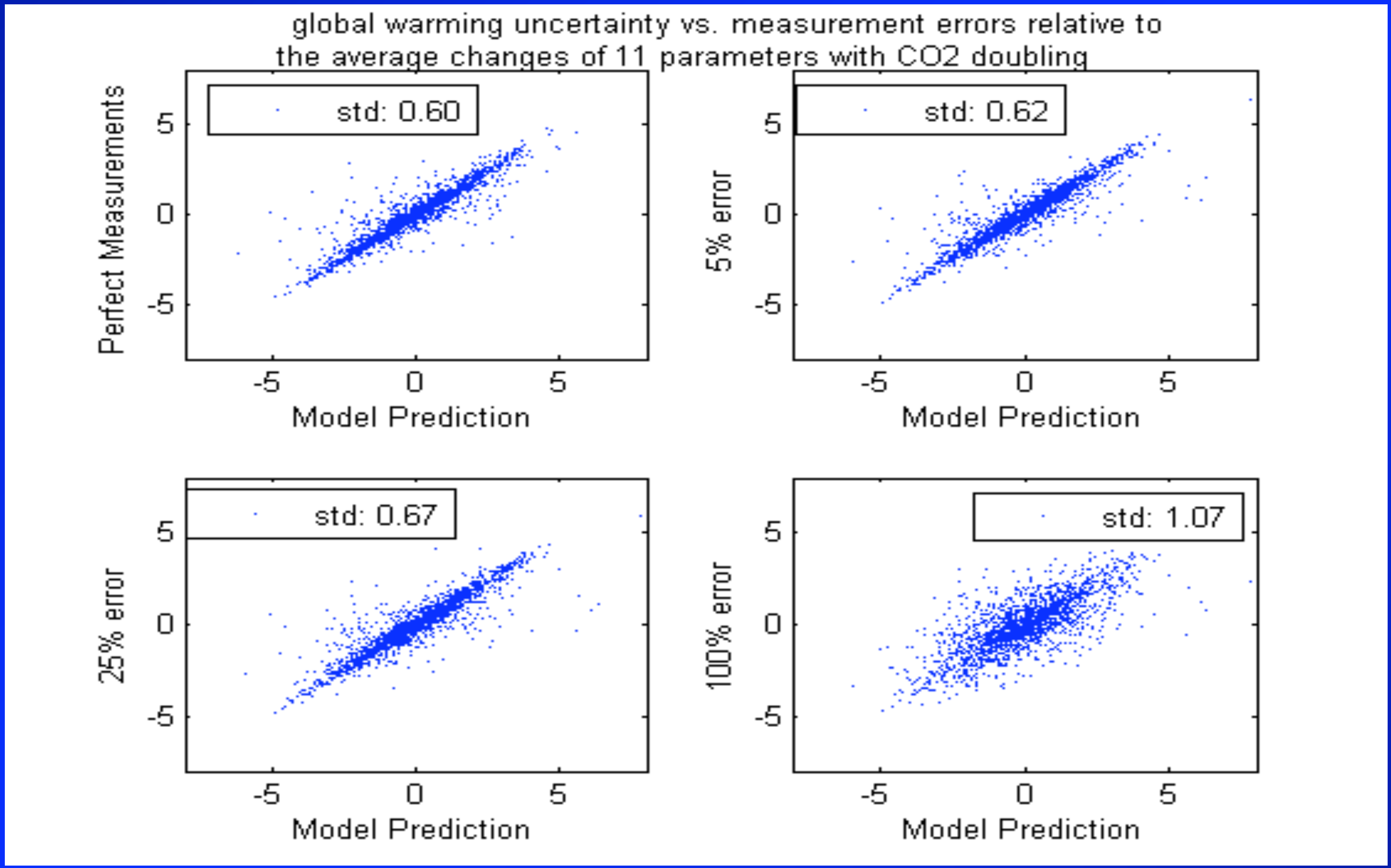
Full Swath Satellite Data (CERES Terra)

CLARREO Single Satellite Nadir 100km Field of View

Spatial sampling errors exceed magnitude of the mean field, Residual nadir only viewing angle biases also evident (e.g. subtropical ocean)

Effect of Observation Error on Neural Net Prediction Accuracy (2xCO_2, Deg C)

(error specified as % of mean 2xCO_2 change for any variable)



If no observation constraint: sigma 1.5 K

Neural Net Results vs. No. of Variables

- Doubling CO_2 Global Temperature Uncertainty (1σ)
  - 33 variables 0.41K
  - 11 variables 0.66K
  - 4 variables 0.89K
- Four variables with largest constraint on climate sensitivity
  - Top of atmosphere shortwave reflected flux
  - Total cloud fraction
  - Convective cloud fraction
  - Total precipitation
- Neural net roughly 2.5 times more accurate than multiple linear regression

Y. Hu, B. Wielicki, M. Allen

Outline

- **Why do we need a NIST in orbit?**
  - Climate change is more powerful metric than base climate state
  - Examples from Loeb et al., surface fluxes, regional ISCCP/CERES diffs
  - Examples from ocean heat storage, CRF vs Cloud Feedback, IPCC.
  - Temp and water vapor trends reports, IPCC aerosol, cloud.
  - Climate change reqmts typically 0.1 to 0.5% per decade (Ohring et al)
  - Overlap and calibration of all satellites is very expensive
  - Examples of GOES changes, vis/ir, CERES, LDEF, GOME, MODIS.
- **Why is calibration an 8^{+} dimensional challenge?**
  - x,y,z,t,vzen,vaz,solzen,wavelength are 8. stealth dimension is calibration absolute accuracy/stability
  - Examples of SW/LW flux variability vs time/space scale
- **Why is CLARREO relevant to NIST in orbit?**
  - Space/time/angle/wavelength matching requirements
  - Spatial matching variable radiance fields: spatial response function
  - Spatial matching variable radiance fields: 1km to 140km matching
  - Angle matching requirements using CERES ADMs
  - Wavelength matching is CLARREO's strength if 0.3 to 50um.

Outline: part II

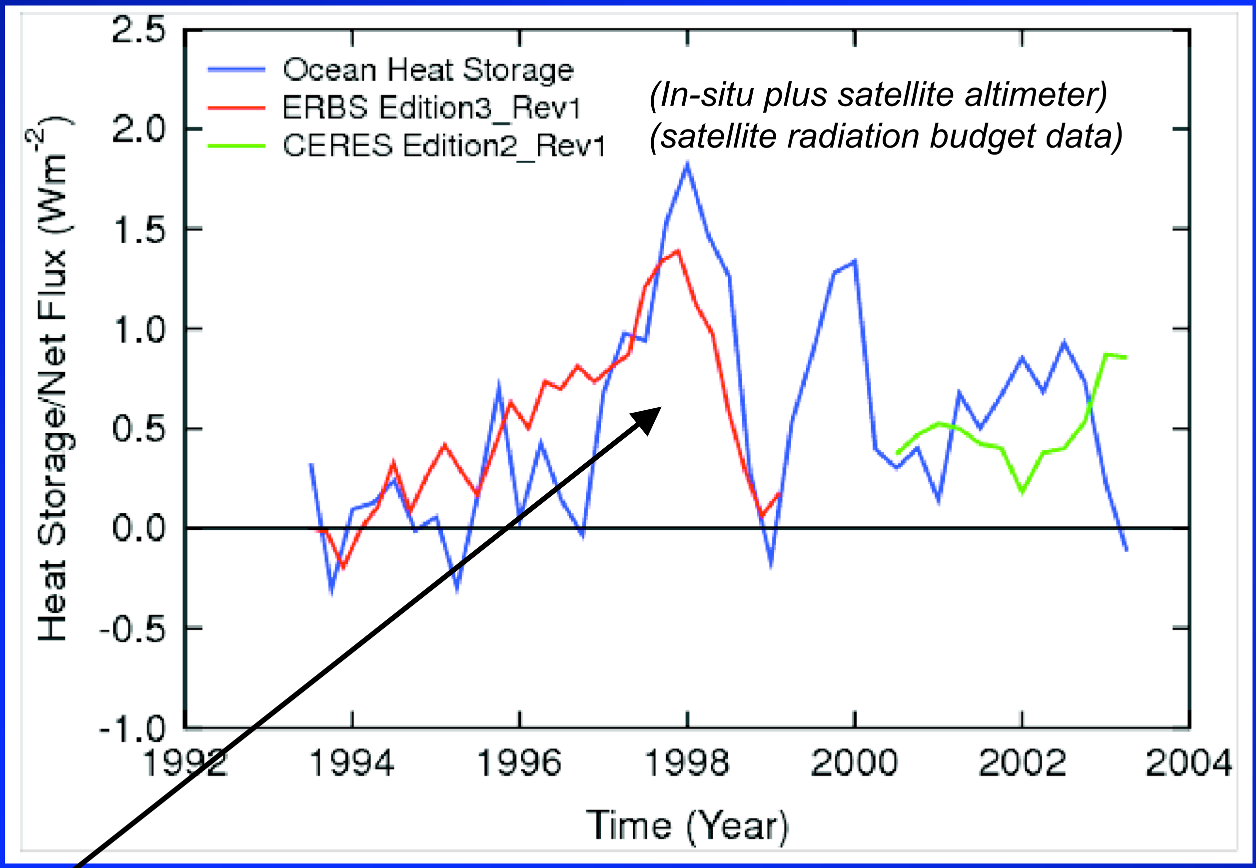
- What are appropriate CLARREO as Calibrator Orbits?
  - The geometry: CLARREO 100km fov spectrometer & NPP/NPOESS etc
  - Precessing orbits: allow orbit crossings of CLARREO with all satellites from leo to geo.
  - 3-month time goal for calibration sampling: verify any seasonal (beta angle) systematic thermal issues, constrain any sudden calibration shifts
  - Need calibration matches from equator to polar ice caps to test in all climate regimes and under a complete range of surface/atmosphere states (e.g. allows testing for any systematic spectral differences)
  - Desire integer number of precession cycles per year: so avoid any diurnal cycle/seasonal cycle aliasing of conditions.
  - Show examples of the simplest cases first:
    - 750 km altitude, nadir to nadir orbit matches within +/- 5 minutes
    - 90 degree CLARREO orbit (1.1 precession cycles per year)
    - 73 degree inclination orbit (2 precession cycles/yr)
    - 63 degree inclination orbit (3 precession cycles/yr)
    - 53 degree inclination orbit (4 precession cycles/yr)

Outline: part III

- What are appropriate CLARREO as Calibrator Orbits? Con't
  - So what 2 sigma goals can we reach with nadir only, linear regression?
  - Mean, slope, offset confidence
  - Trend detection confidence
  - How could we improve sampling:
    - If allow pointing of spacecraft or instruments (not scan, just point)
    - +/- 50 degree scan angle matches in an orbit crossing, with every 100km fov separated by 100km could provide 10-20 samples, not one at nadir.
    - Time to match scan angles is a function of altitude difference of the two spacecraft: linear at roughly 40 seconds per 100km orbit altitude difference
    - Suggests 500km orbit: 1000km may have too much radiation exposure for instrument lifetime. At 500km CLARREO altitude, would have 340km difference from NPOESS, 200km from Terra/Aqua: so 135 seconds and 80 seconds respectively. Would require spacecraft or instrument pointing of roughly 1 to 2 degrees per second.
    - Would also allow pointing off nadir to view up to 83 degrees latitude for higher latitude polar observations using a 73 degree inclination orbit (2 precession cycles per year).

Global Net Radiation and Ocean Heat Storage

large variability shows a cloud forcing & ocean heating link
(aerosol changes are too small)



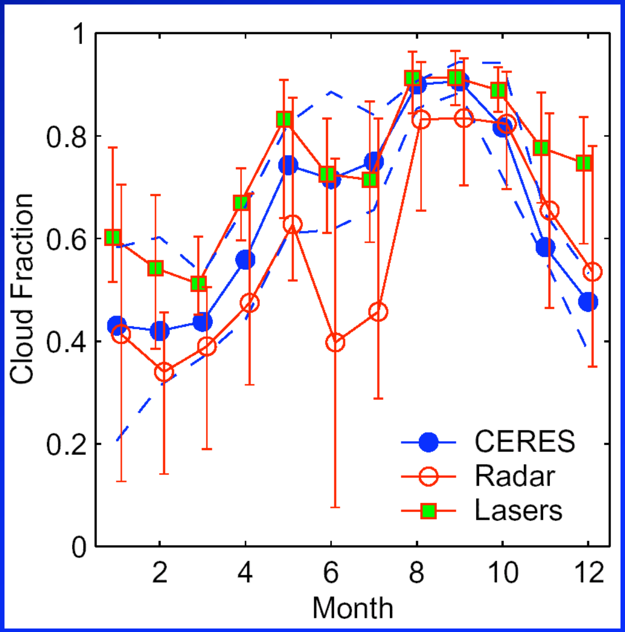
Wong et al.,
2006 J. Climate

Variability in global ocean heat storage is larger than anthropogenic radiative forcing of 0.6 Wm^{-2} per decade. Satellite data and in-situ annual ocean data agree to 1σ of 0.4 Wm^{-2}, equal to the in-situ spatial sampling noise. Decade average ocean heating consistent with IPCC climate models (Hansen et al., 2006)

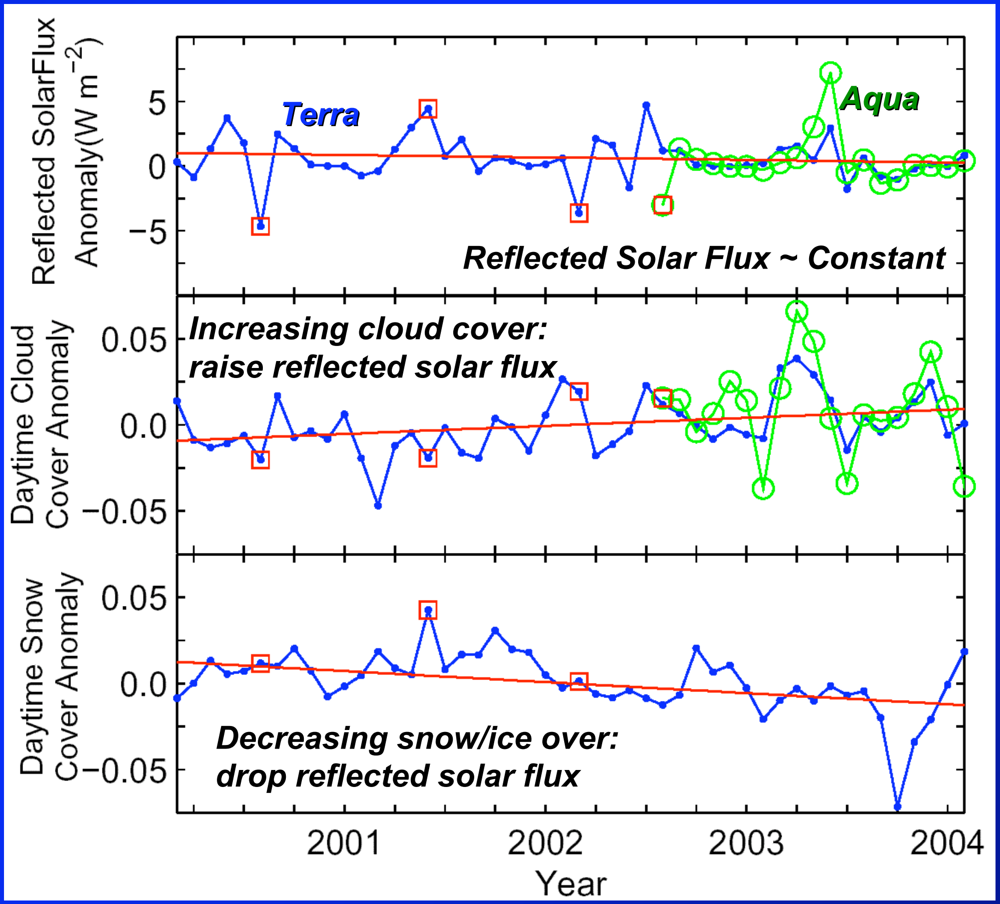
Arctic Warming: Are clouds offsetting much of the positive feedback of decreasing snow and ice?

Arctic (60N-90N) Trends from Terra & Aqua

Cloud Fraction at Barrow Alaska



CERES cloud analysis using MODIS data shows new polar cloud data compares well with surface lidar & radar from the DOE ARM site

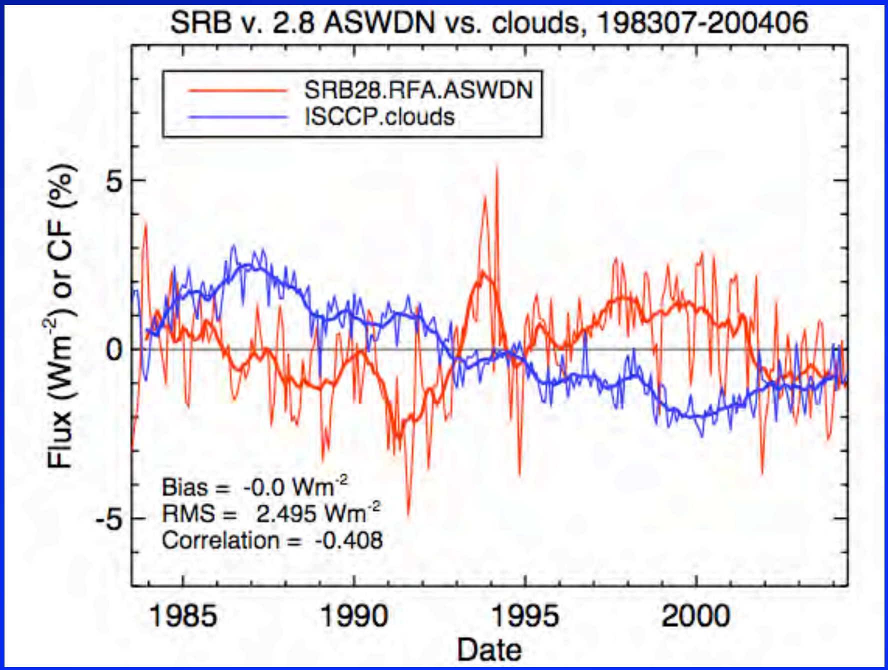


Currently, increasing Polar cloudiness is offsetting most of the positive climate feedback of decreasing Arctic snow and ice.
Will it continue?

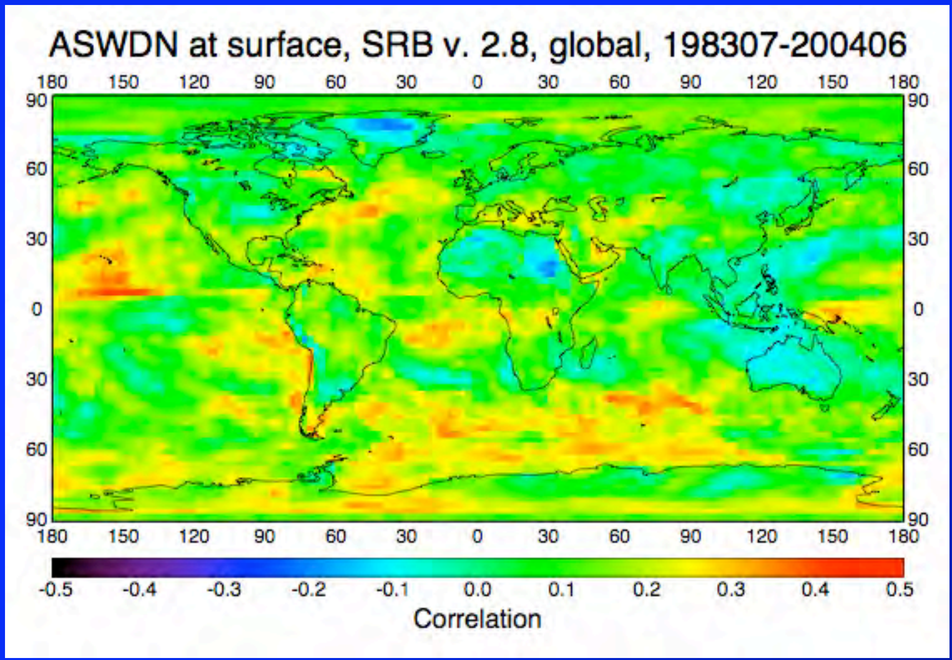
Kato et al., GRL, 2006

ISCCP Cloud Cover Artifacts

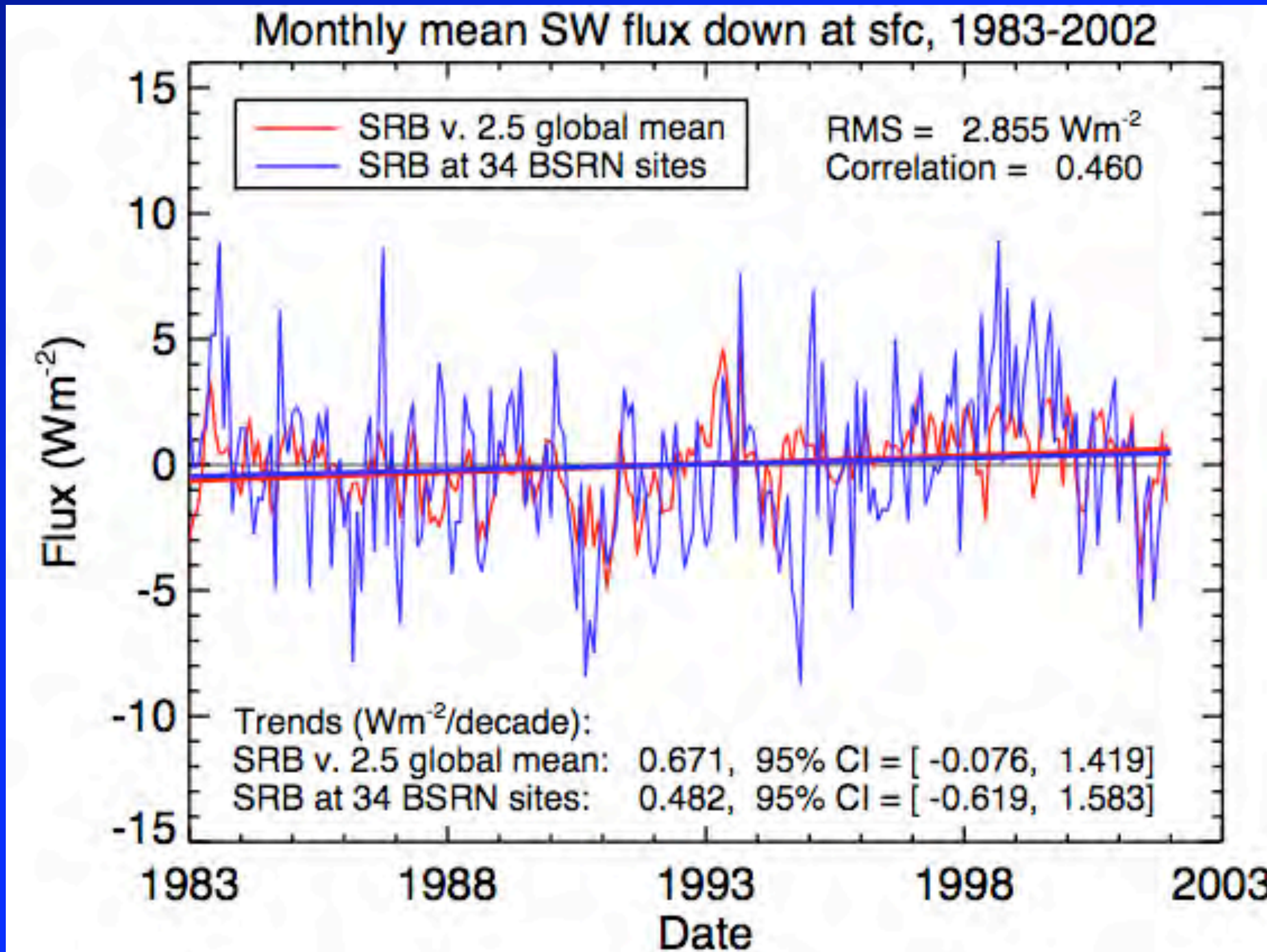
SRB Mean Downward SW Flux



Local Correlation to Mean



Data analysis



Outline: part IV

- What about diurnal cycles?
  - Primary issue was aliasing drifting polar orbiters (e.g. NOAA, MSU)
  - All new polar orbiters since 2000 use controlled orbits: same local time of day sampling during the entire mission. aliasing now secondary
  - So what fraction of climate change/anomalies are diurnal cycles versus mean fields? For SW and LW: about 1/4 are diurnal cycle and 3/4 are mean field. Show geo/nongeo examples.
  - Solar diurnal cycles are larger by a factor of 3 than LW.
  - CLARREO has 1 solar diurnal cycle orbit and 3 infrared orbits. Not good for benchmark radiance sampling in solar.
  - Suggests need CLARREO Primarily as Calibrator: 2 orbits with LW/SW
  - But because narrowband filters vary instrument to instrument, CLARREO is also needed as benchmark radiance time series when not calibrating other instruments (90% of time in nadir benchmark mode)
  - BUT: solar nadir spectral radiance is poorly linked to solar spectral reflected flux (ADMs): SW anisotropy is 3 to 4 times the problem that LW is.

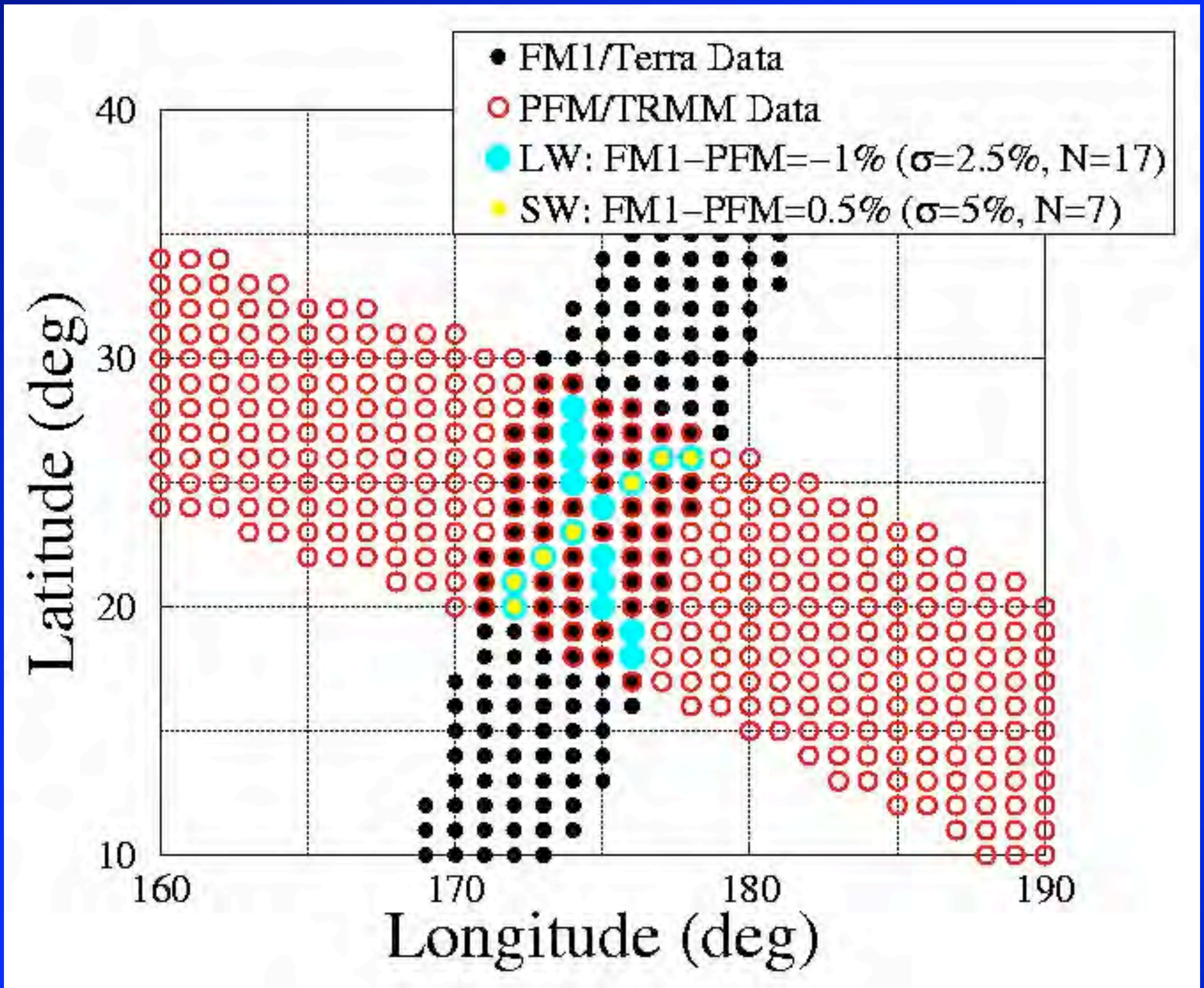
Outline: part V

- What about changing narrowband spectral response functions?
  - Jim Anderson is right: narrowband filters vary from instrument to instrument. As a climate record it MUST be corrected.
  - One method would be to fly CLARREO in all climate regimes as a calibrator mission, then use CLARREO benchmark radiance observations to determine impact of spectral differences for all climate regimes (simulate both different channels with CLARREO spectrum and then show differences over a full annual cycle). Then use theory to do the same (i.e. change filter response) and agreement shows we understand both the physics and the observation. If not: investigate the differences by climate regime, surface type, gas absorbers, etc
- What would it take to get a solid SW spectral flux benchmark record from CLARREO?
  - ADMs dominate the problem. Only have well observed broadband CERES SW, LW ADMs: rest would be theory (not better than several %) ADMs and calibration become accuracy limit. NOT SI.
  - Full hemispheric scan would be MUCH larger instrument: estimate scaling CERES ADM sampling to CLARREO fovs: samples per second and pointing rate needed?

Outline: part VI

- What is the spatial sampling noise of nadir only?
  - Use ERBE 60km fov nadir vs full swath
  - 2.5 degree region, 2.5 lat by 30 deg long, zonal, global
  - Compare to climate anomaly magnitudes
  - Signal to noise from sampling?
  - This is not an issue using CLARREO as Calibrator First, and Benchmark Radiance Second (really a spectral mismatch transfer observation).

Satellite Overpass Intercalibration



CERES has developed this capability for:

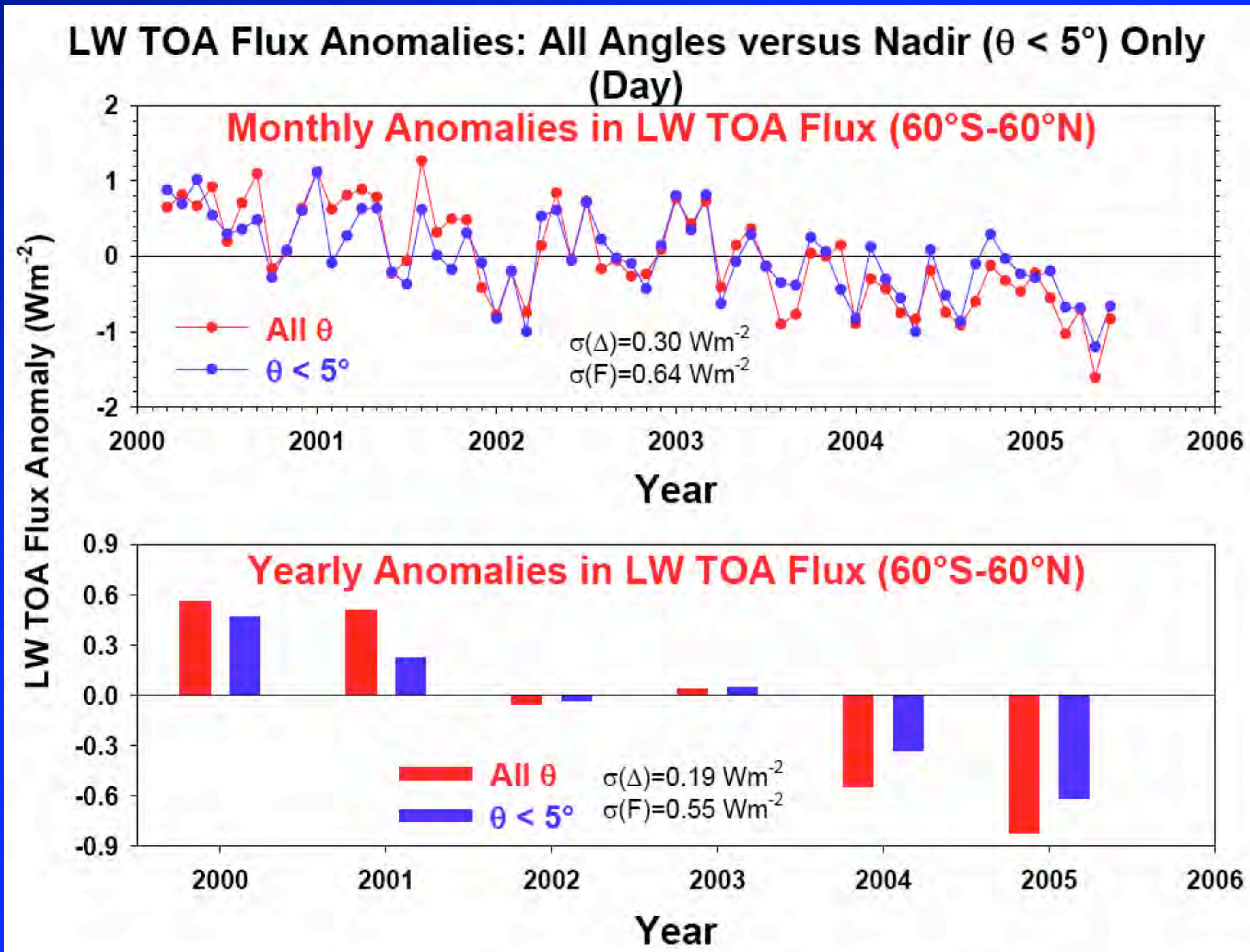
- *CERES/GERB/ScaRaB*
- *TRMM/Terra/Aqua*
- *MODIS/VIRS/Geo imagers*
- *Geo/Precessing/Sunsynch orbits*
- *Not only nadir: all angle matches*
- *Needed for data fusion as climate data record*

Outline: part V

- Following Telecon with Jim/Bill
  - Bill will cover climate models, IPCC report, need for spectral radiance metrics (CPDN version?) Signal emerging from noise. Davidoff sensitivity paper? Unclear on solar
  - Jim explain NRC process, structure, prioritization, ASIC3, IR spectra are independently verified against GPS temperature record as "absolute". Forcing/response for IR temperature, humidity, cloud IR, IR instrument design, diurnal sampling, Solar measurements (lunar calibration using NIST high altitude long duration balloon. Violates mutl-point calibration though: no nonlinearity, cannot separate gain/offset, etc.
  - My Outline on the telecon:
    - climateprediction.net base state vs climate change metrics
    - IPCC aerosol forcing factor of 3, temp/water vapor well known, cannot constrain sensitivity with deltaT/deltaF
    - IPCC cloud feedback largest sensitivity uncertainty: factor of 2.5 to 3 and low cloud: changing albedo of the planet and its temperature "set point"
    - IPCC global temperature signal doesn't separate until 2050: less vs more sensitive models: must resolve in sw and net cloud radiative forcing, cloud properties, separate indirect effect/cloud feedback.
    - CERES/SeaWiFS/MODIS showing first interannual variations at climate accuracy
    - Earthshine and dimming problematic (poor accuracy/sampling, regional variability
    - CERES/surface sites showing interannual variations at climate accuracy
    - Absolute accuracy remains too coarse: plot of LW flux differences
    - NPOESS is going backwards with VIIRS calibration from MODIS and MISR and SeaWiFS: NO lunar deep space on NPOESS or NPP.
    - Review Ohring et al requirements and needs
    - We have heard about CLARREO as benchmark: now clarreo as calibrator.

CLARREO IR Benchmark Sampling Error

Nadir 100km vs Full Swath Scan



How Often Will Orbits Cross?

- What about diurnal cycles?

How Close in Time for Calibration Matches?

- What about diurnal cycles?

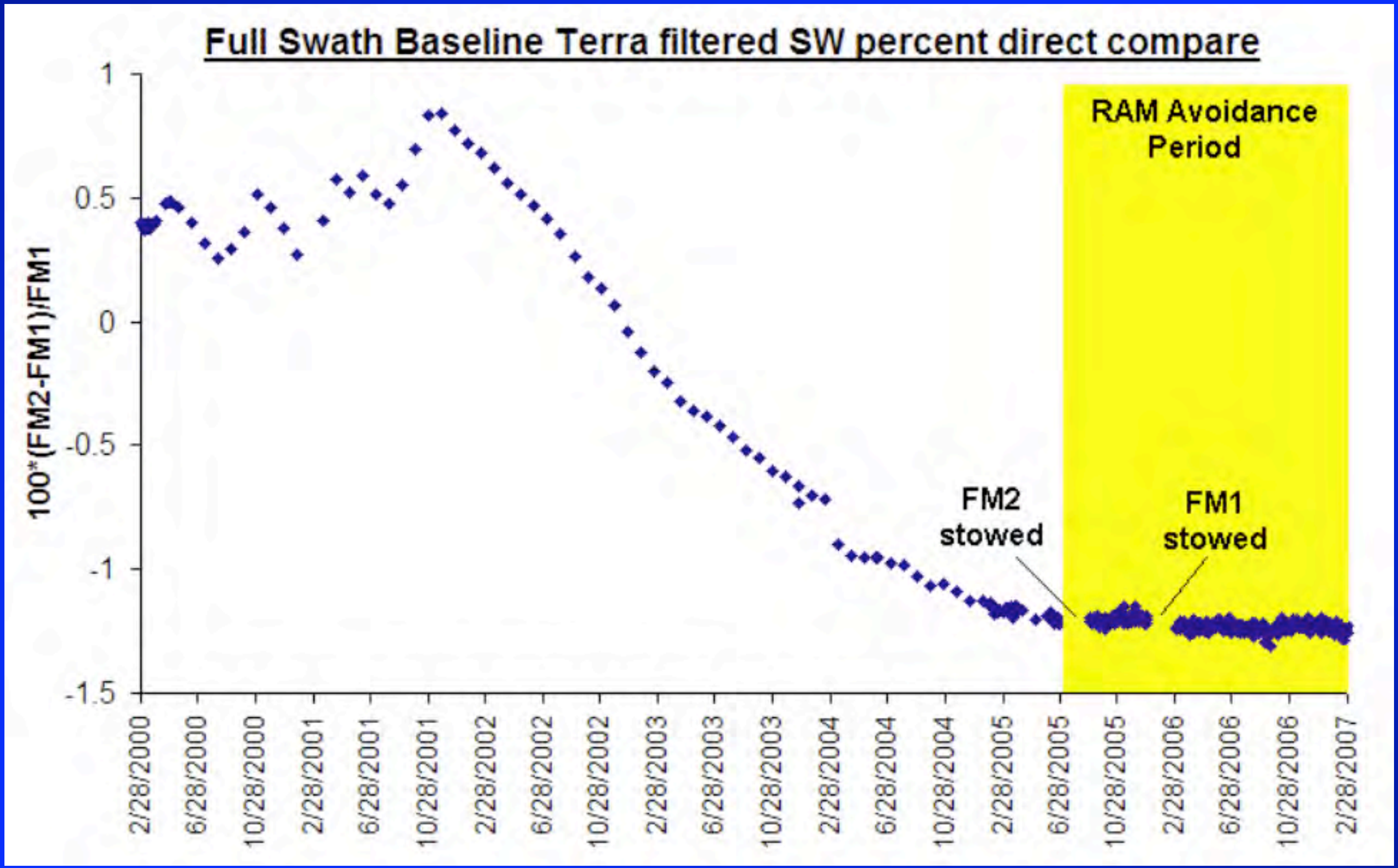
How Close in Angle for Calibration Matches?

- What about diurnal cycles?

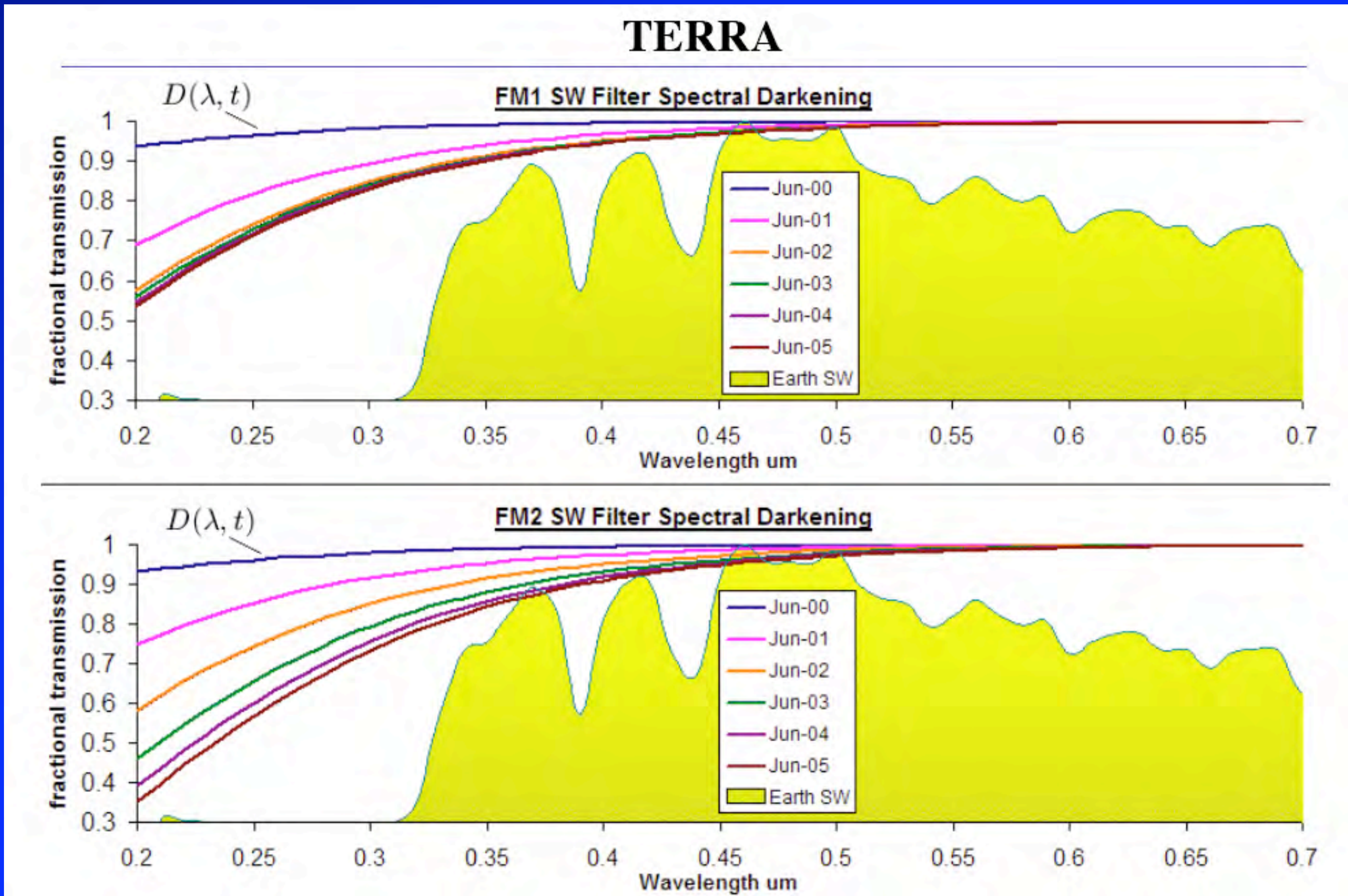
How Often Will Orbits Cross?

- What about diurnal cycles?

Evidence for Solar Optics Contamination in Orbit



Evidence for Solar Optics Contamination in Orbit



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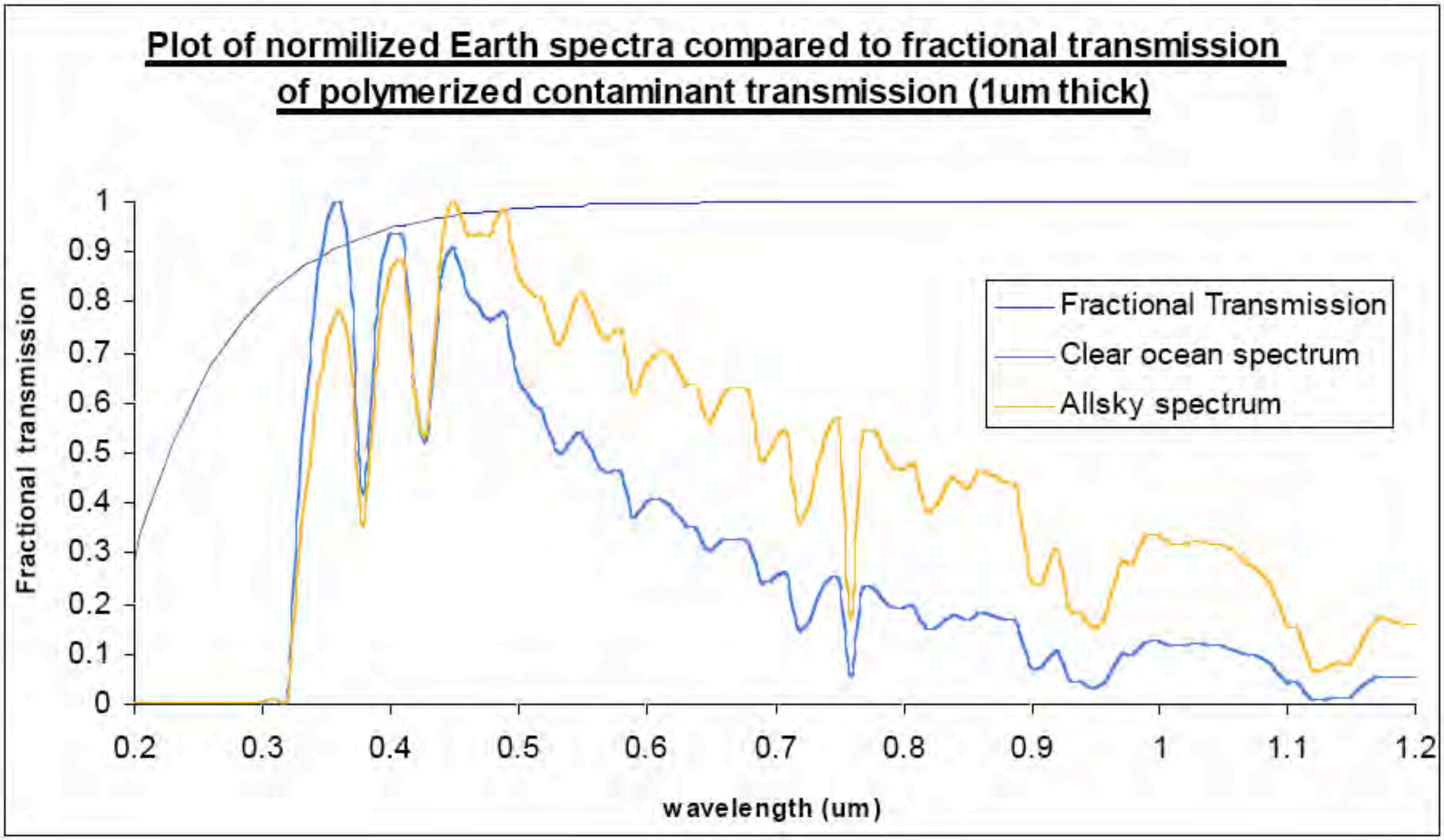

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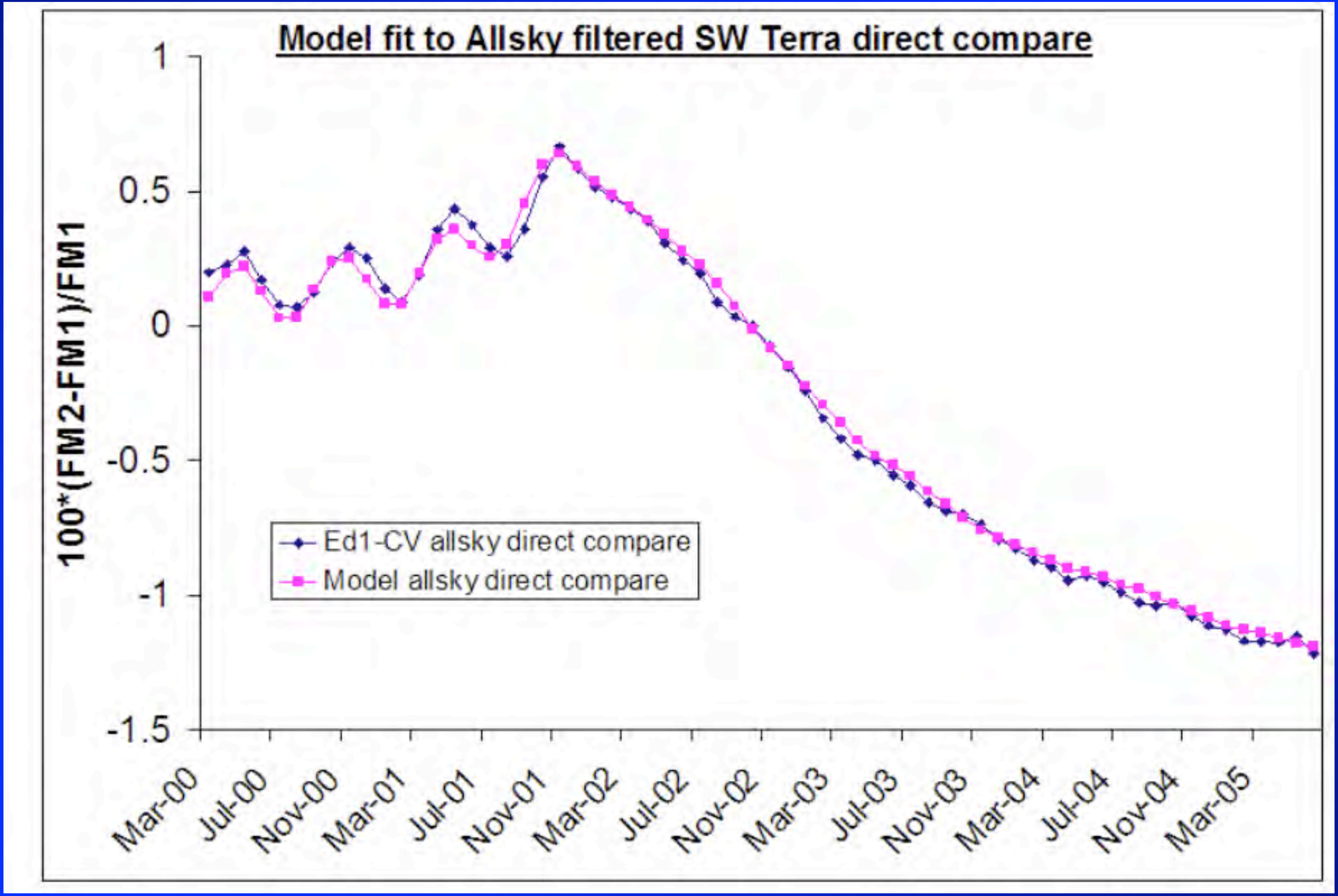
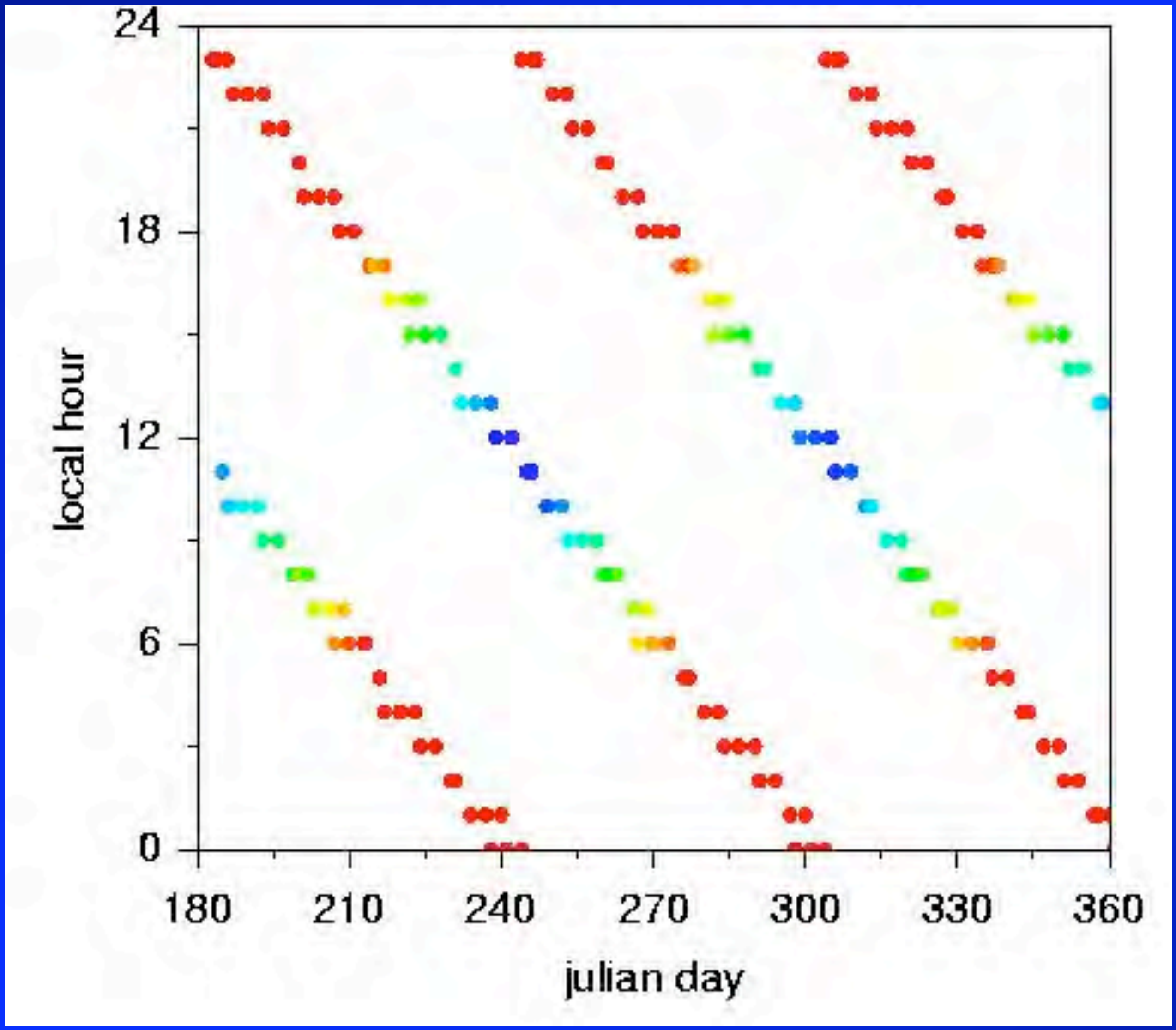


74 degree Inclination Orbit
6 months of Equator Crossing Times



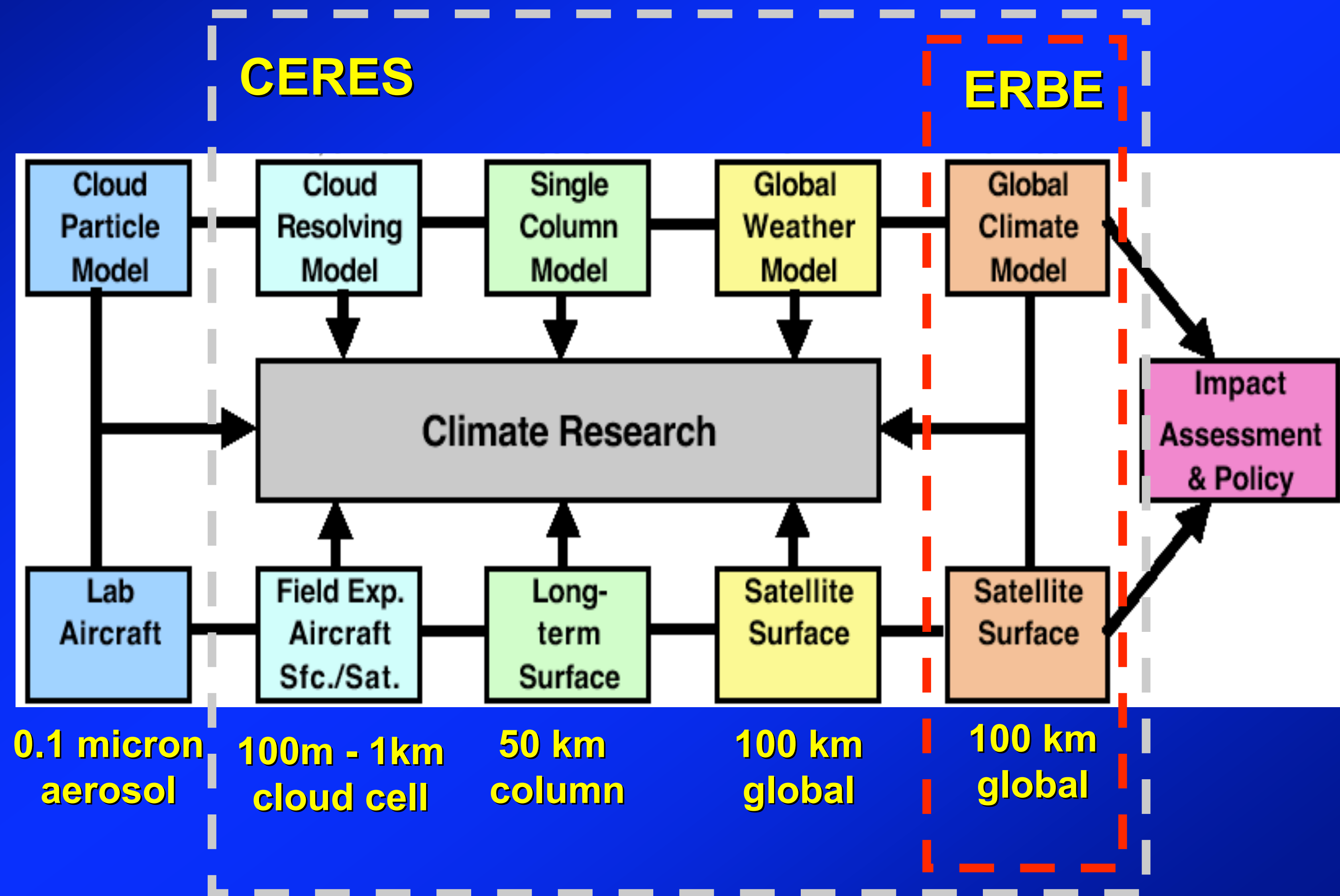
Solar zenith angle in color (blue high sun to red low sun)

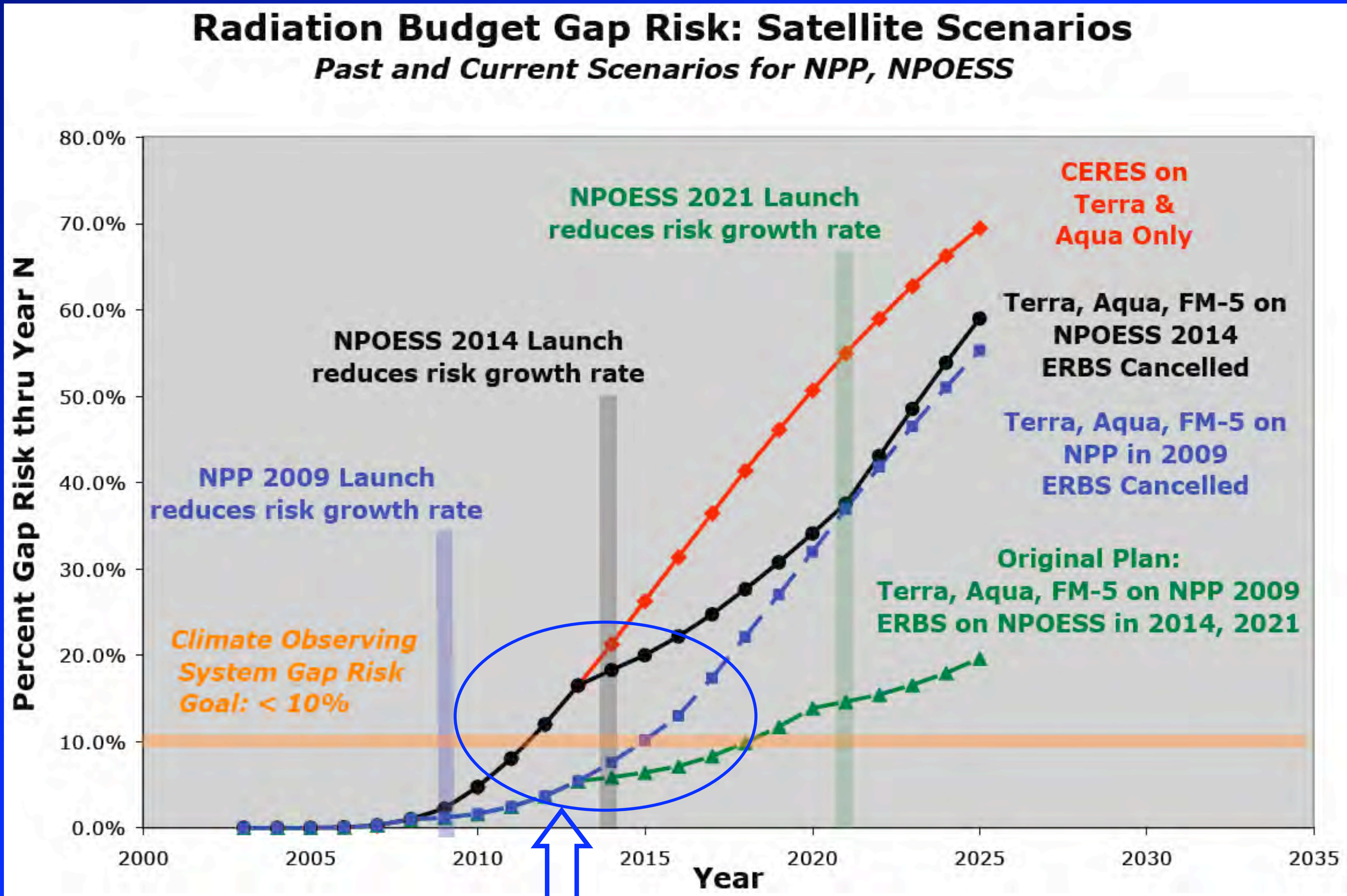
This orbit samples the equator at local noon 6 times per yr.

Nominal CLARREO 90 degree inclination orbit does this twice per year.

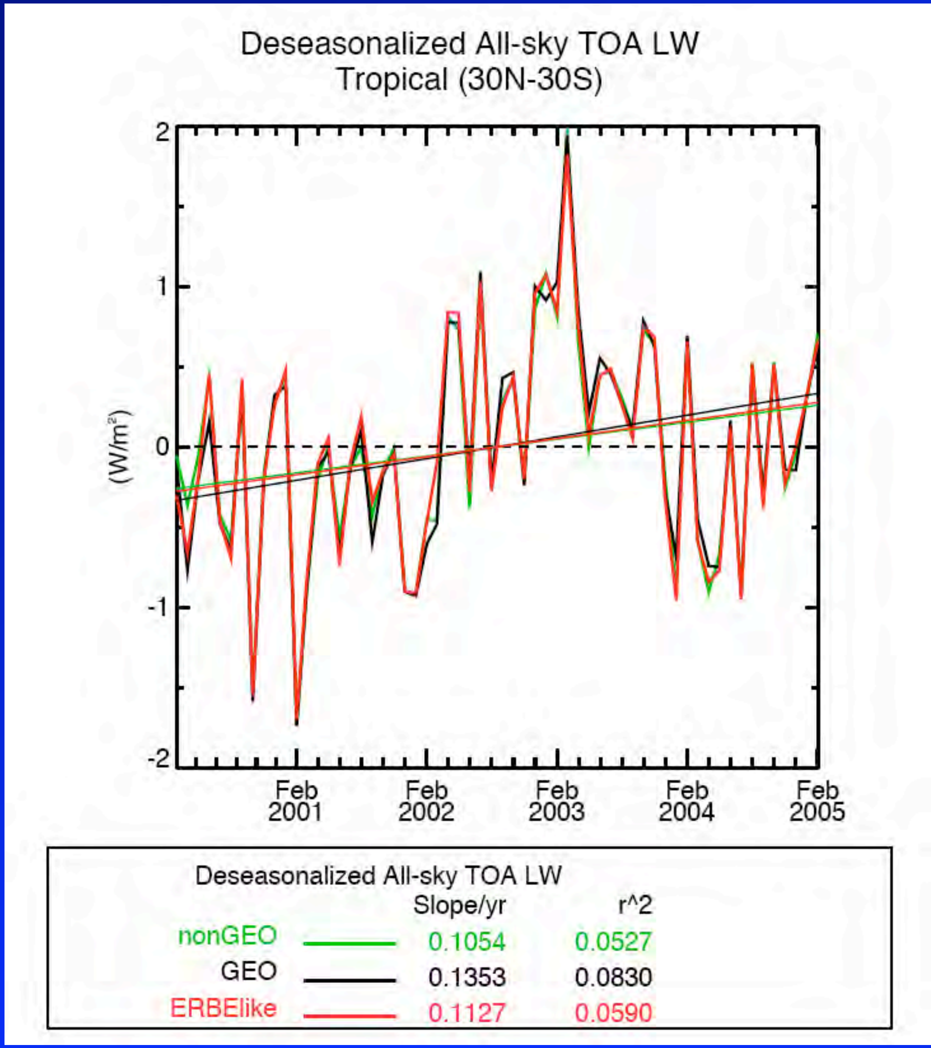
Inclination is max latitude seen at nadir, add 10 deg lat off nadir

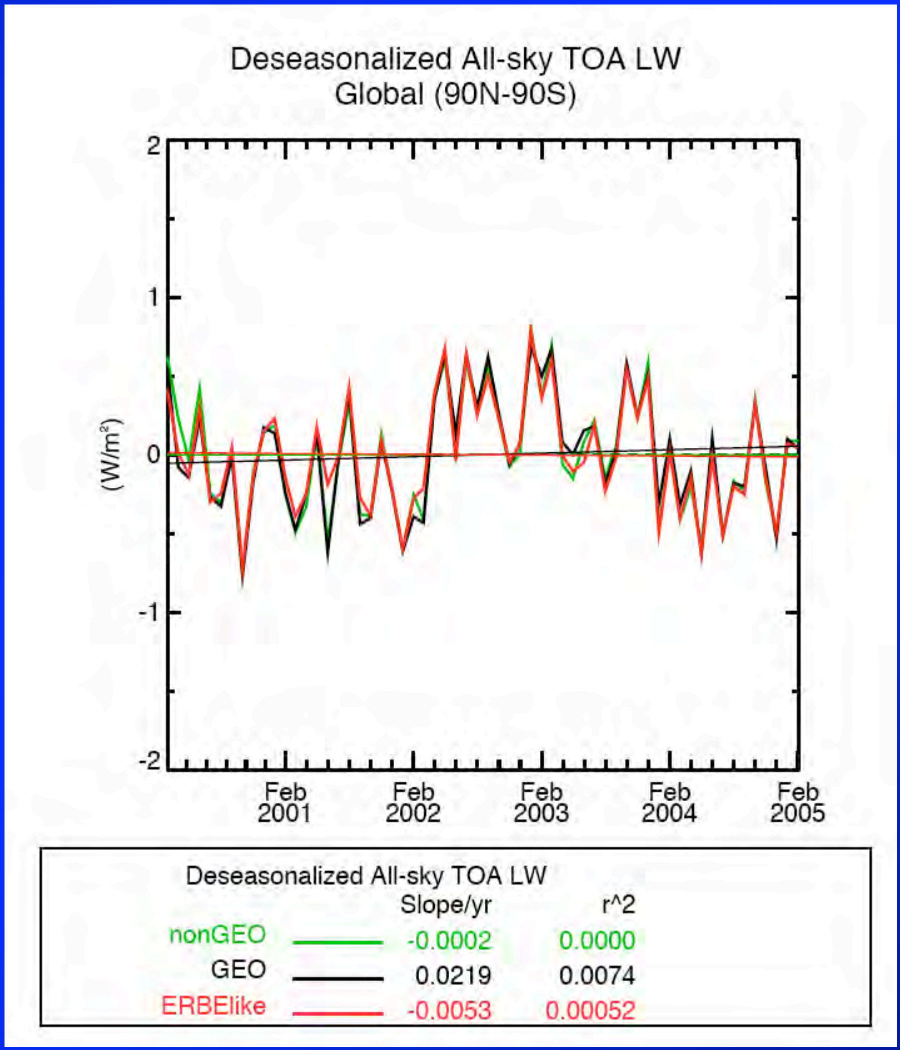
Range of Cloud/Aerosol/Radiation Model Tests



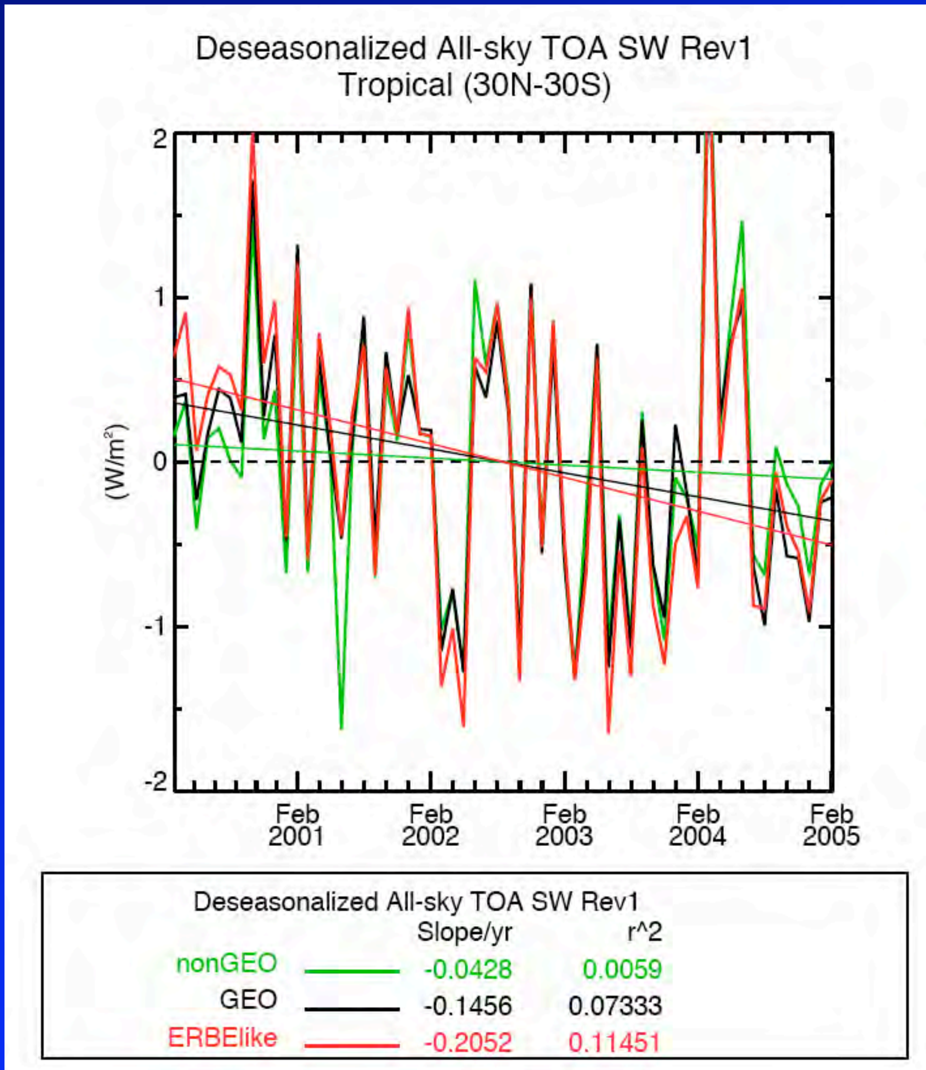


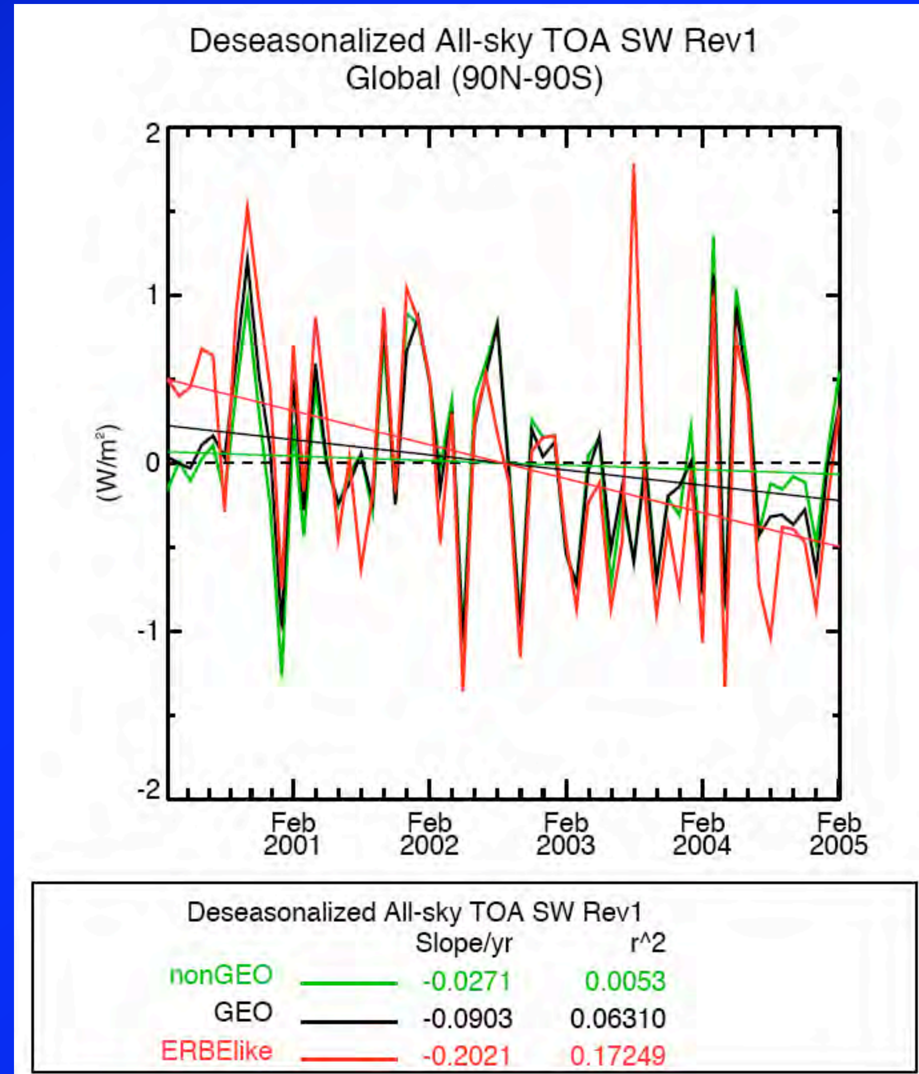
Factor of 3 reduction in gap risk with CERES FM-5 on NPP





Tropical and Global Mean Effect of Diurnal Cycle: Very Small
GEO is CERES + 3-hourly Geo Diurnal Cycle, nonGEO = CERES Terra Only





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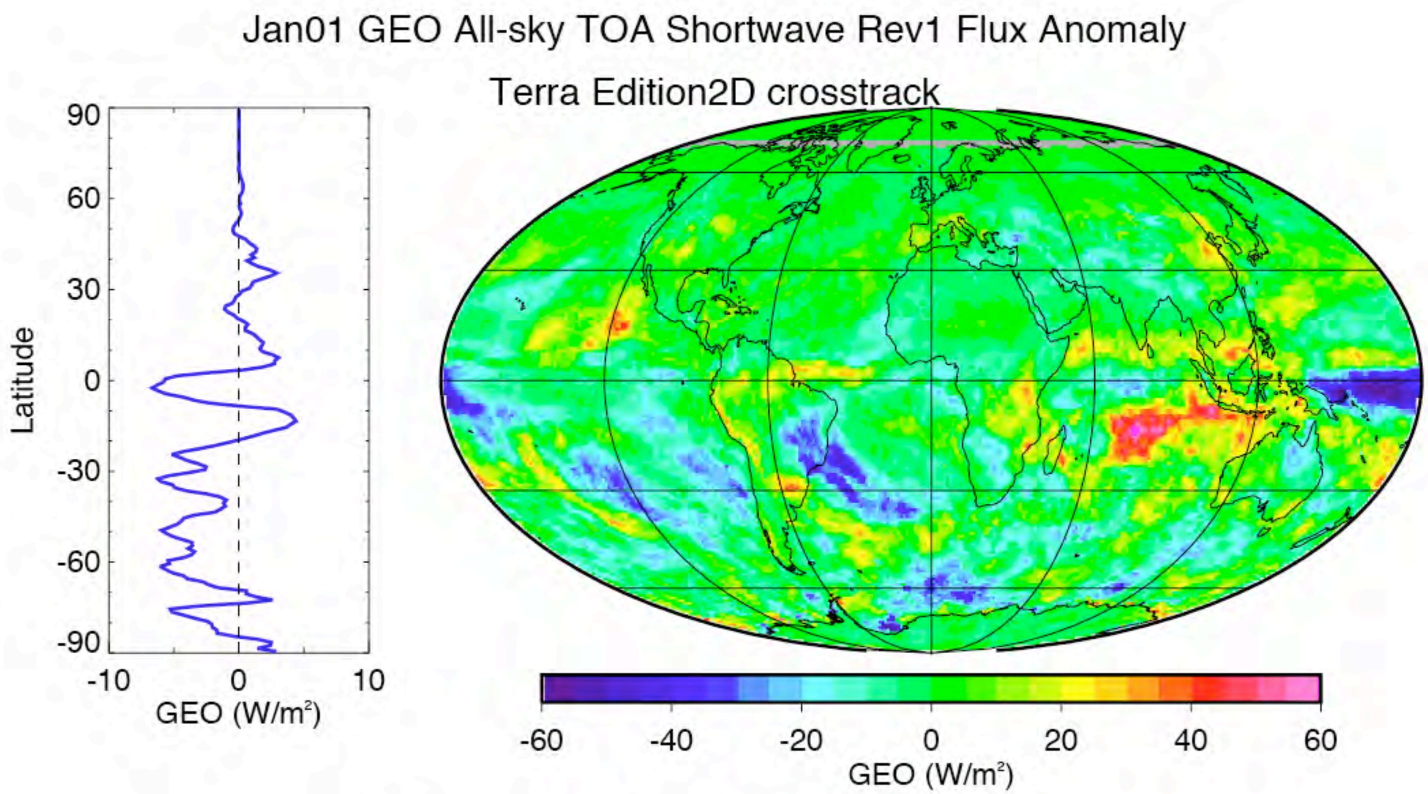
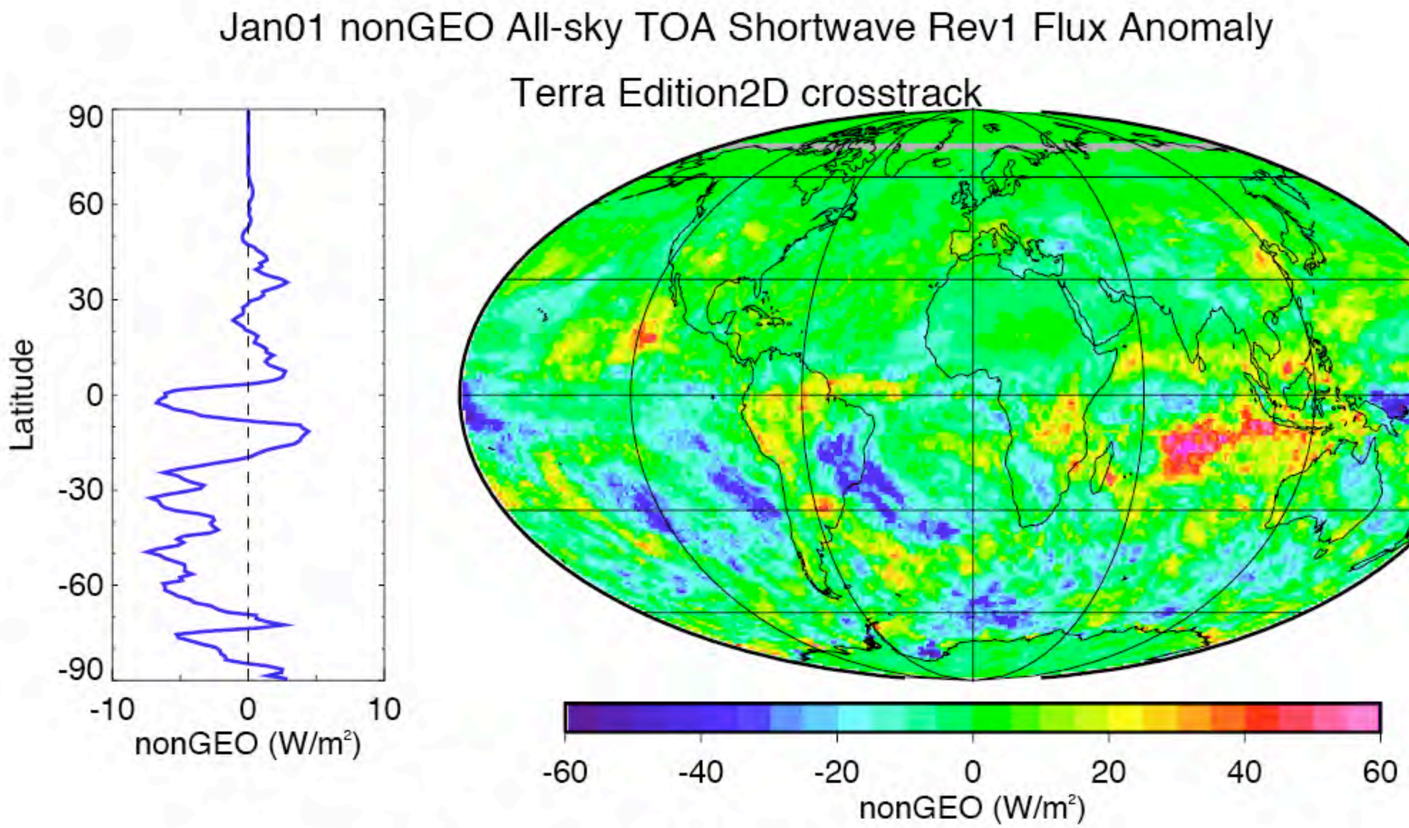


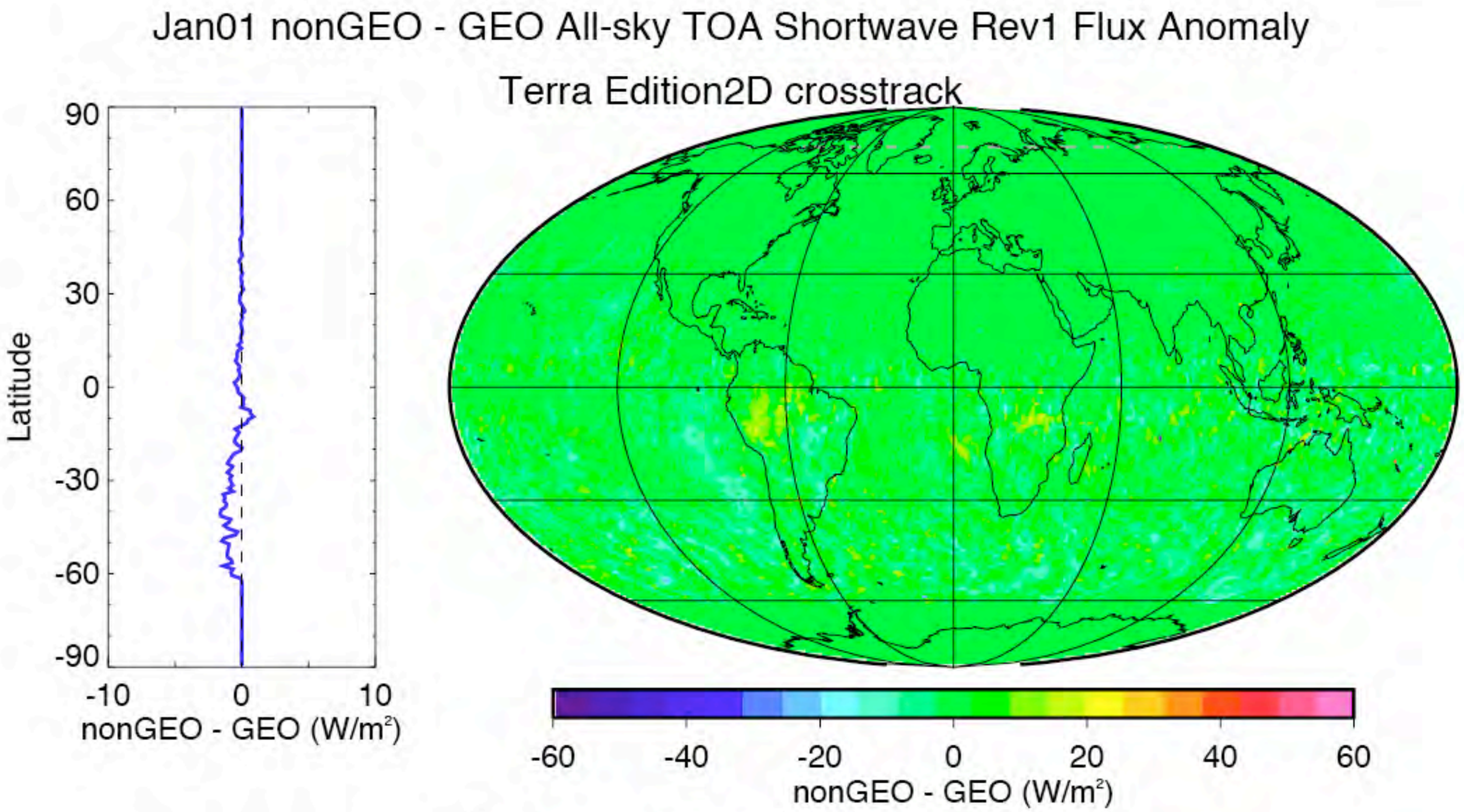
	Jan01	Jan mean	diff
Global	103.01	103.99	-0.97
60N-60S	98.22	99.15	-0.92
30N-30S	92.80	93.29	-0.49

Jan 2001 De-seasonalized SW Flux Anomaly Relative to 2001-2005 Avg
(CERES Terra plus 3-hourly geostationary data for diurnal cycle)



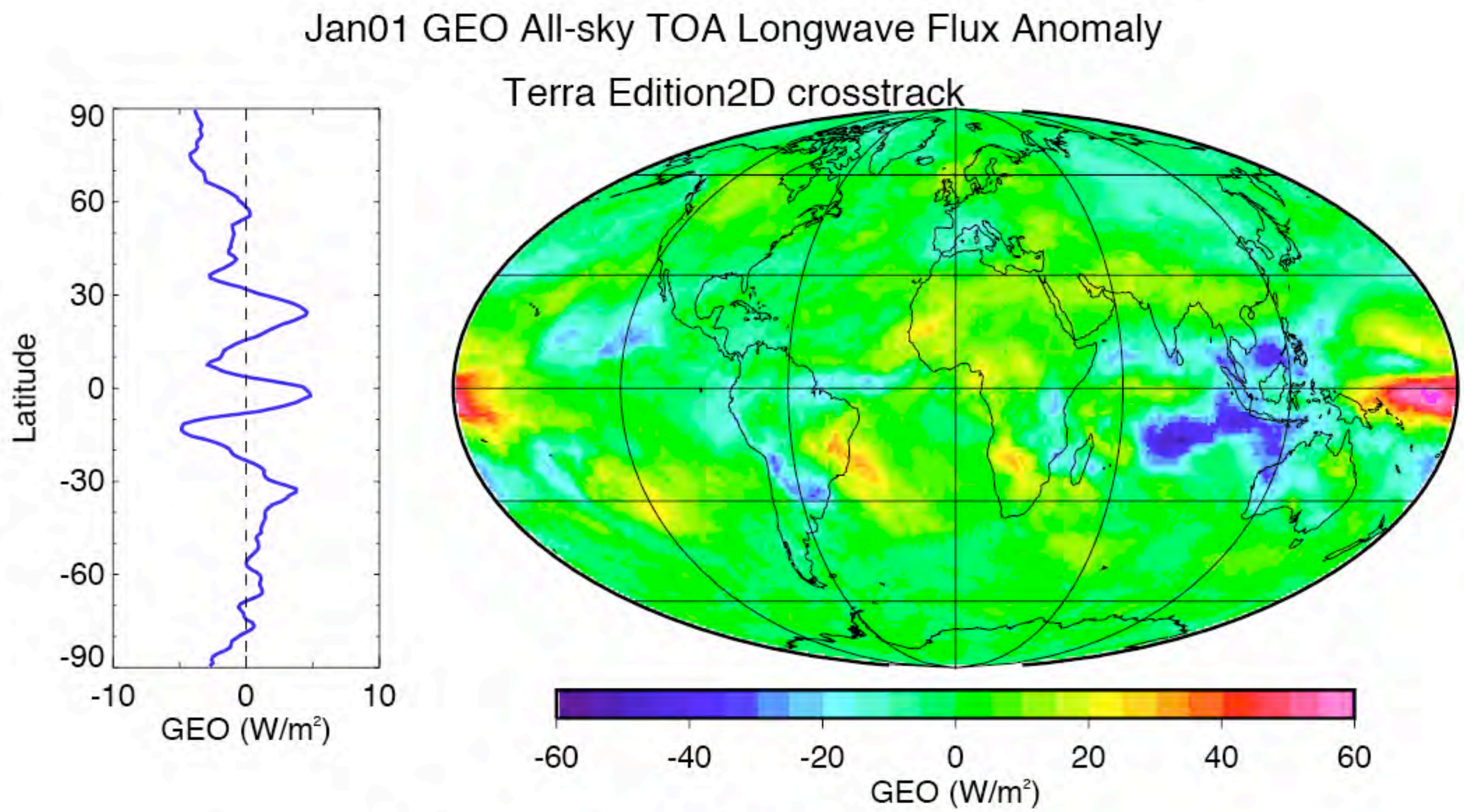
	Jan01	Jan mean	diff
Global	102.17	103.44	-1.27
60N-60S	97.24	98.50	-1.26
30N-30S	91.43	92.11	-0.68

Jan 2001 De-seasonalized SW Flux Anomaly Relative to 2001-2005 Avg
(CERES Terra (1030LT) only for diurnal cycle)



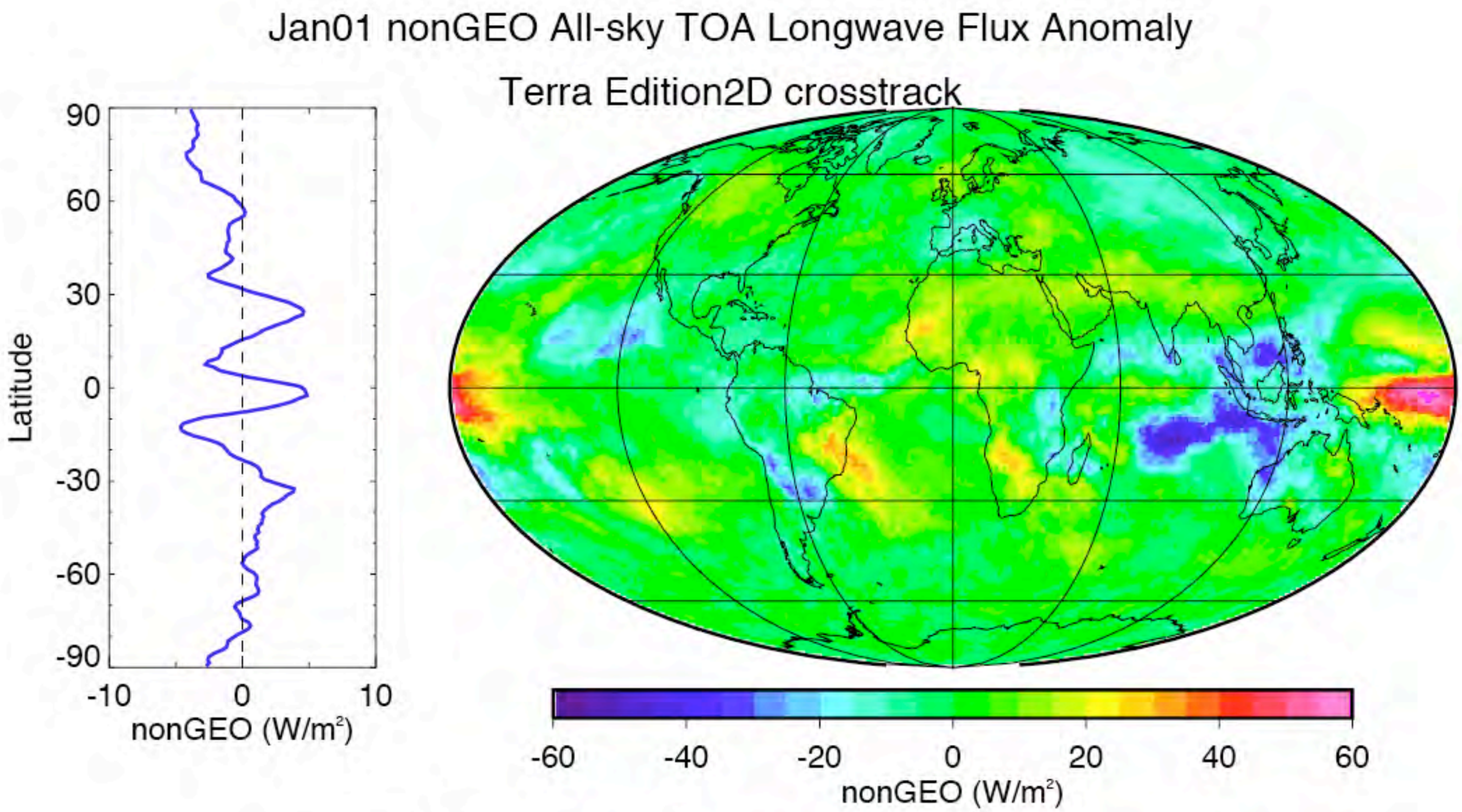
	nonGEO	GEO	diff
Global	-1.27	-0.97	-0.30
60N-60S	-1.26	-0.92	-0.34
30N-30S	-0.68	-0.49	-0.19

Jan 2001 De-seasonalized SW Flux Anomaly Relative to 2001-2005 Avg
(With and Without Geo: Effect of Diurnal Cycle is Small)



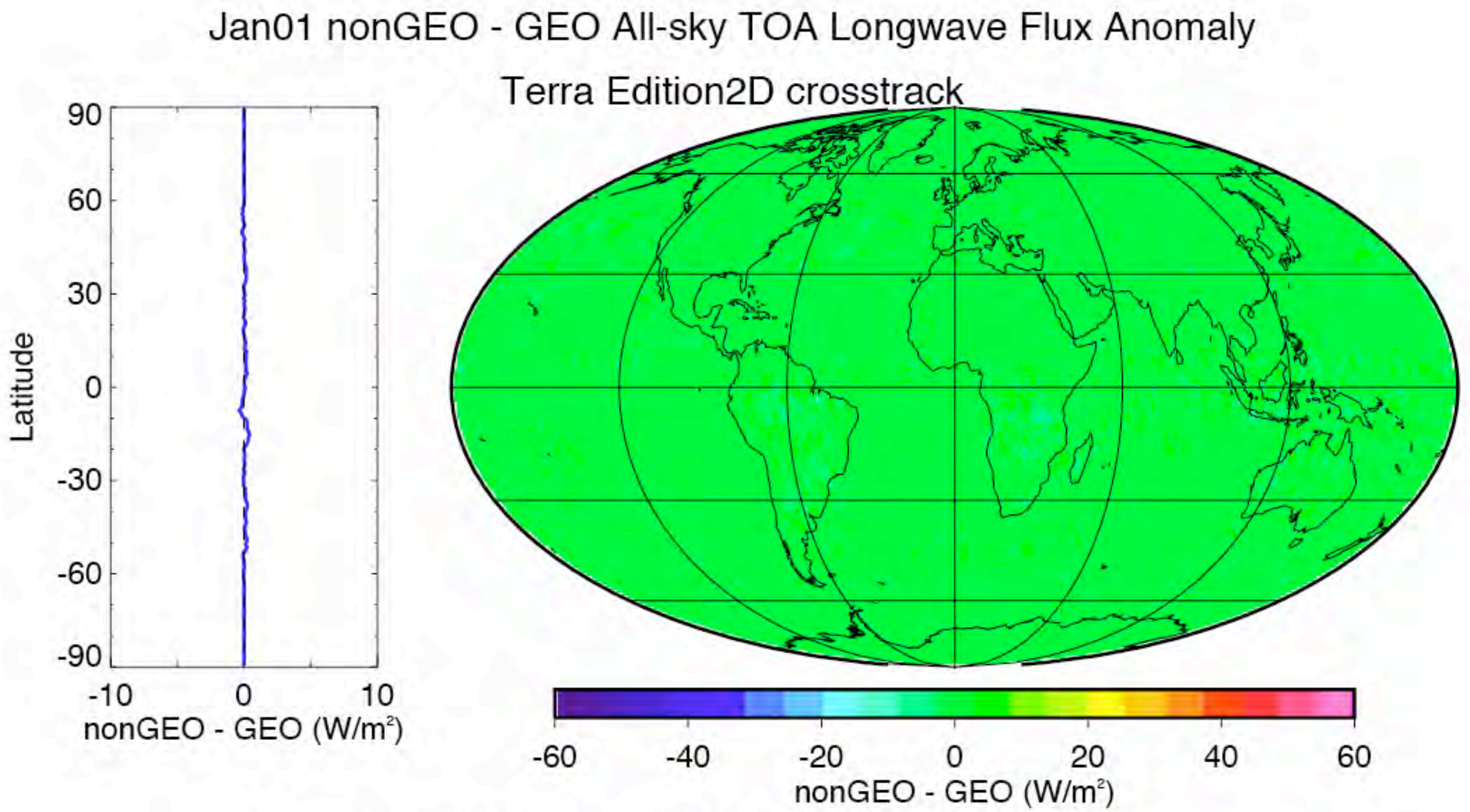
	Jan01	Jan mean	diff
Global	234.18	234.05	0.14
60N-60S	241.30	240.95	0.35
30N-30S	255.55	255.17	0.38

Jan 2001 De-seasonalized LW Flux Anomaly Relative to 2001-2005 Avg
(CERES Terra plus 3-hourly geostationary data for diurnal cycle)



	Jan01	Jan mean	diff
Global	234.71	234.52	0.19
60N-60S	241.91	241.51	0.41
30N-30S	256.50	256.06	0.44

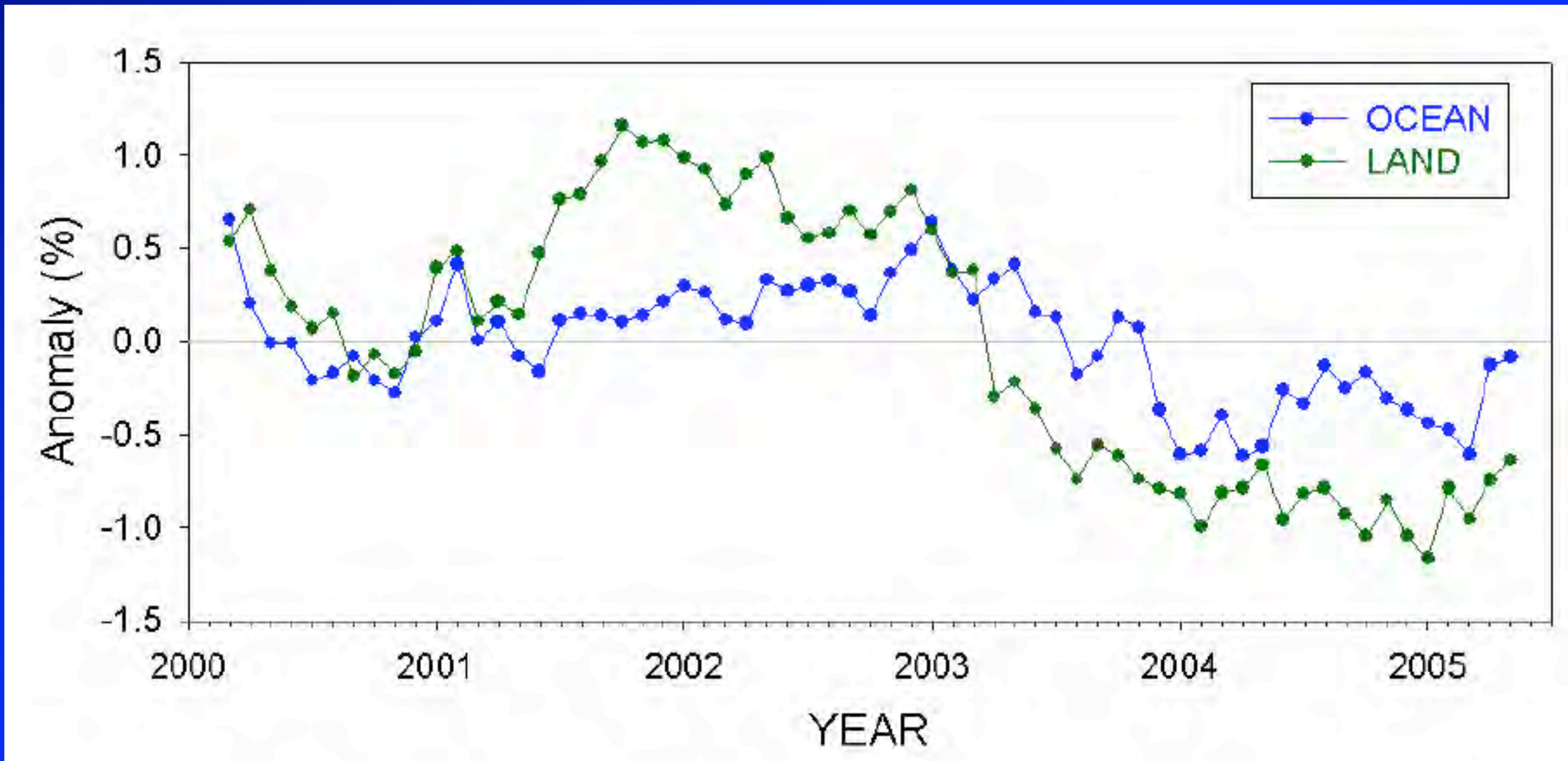
Jan 2001 De-seasonalized LW Flux Anomaly Relative to 2001-2005 Avg
(CERES Terra (1030LT) only for diurnal cycle)



	nonGEO	GEO	diff
Global	0.19	0.14	0.05
60N-60S	0.41	0.35	0.06
30N-30S	0.44	0.38	0.06

Jan 2001 De-seasonalized LW Flux Anomaly Relative to 2001-2005 Avg
(With and Without Geo: Effect of Diurnal Cycle is Small)

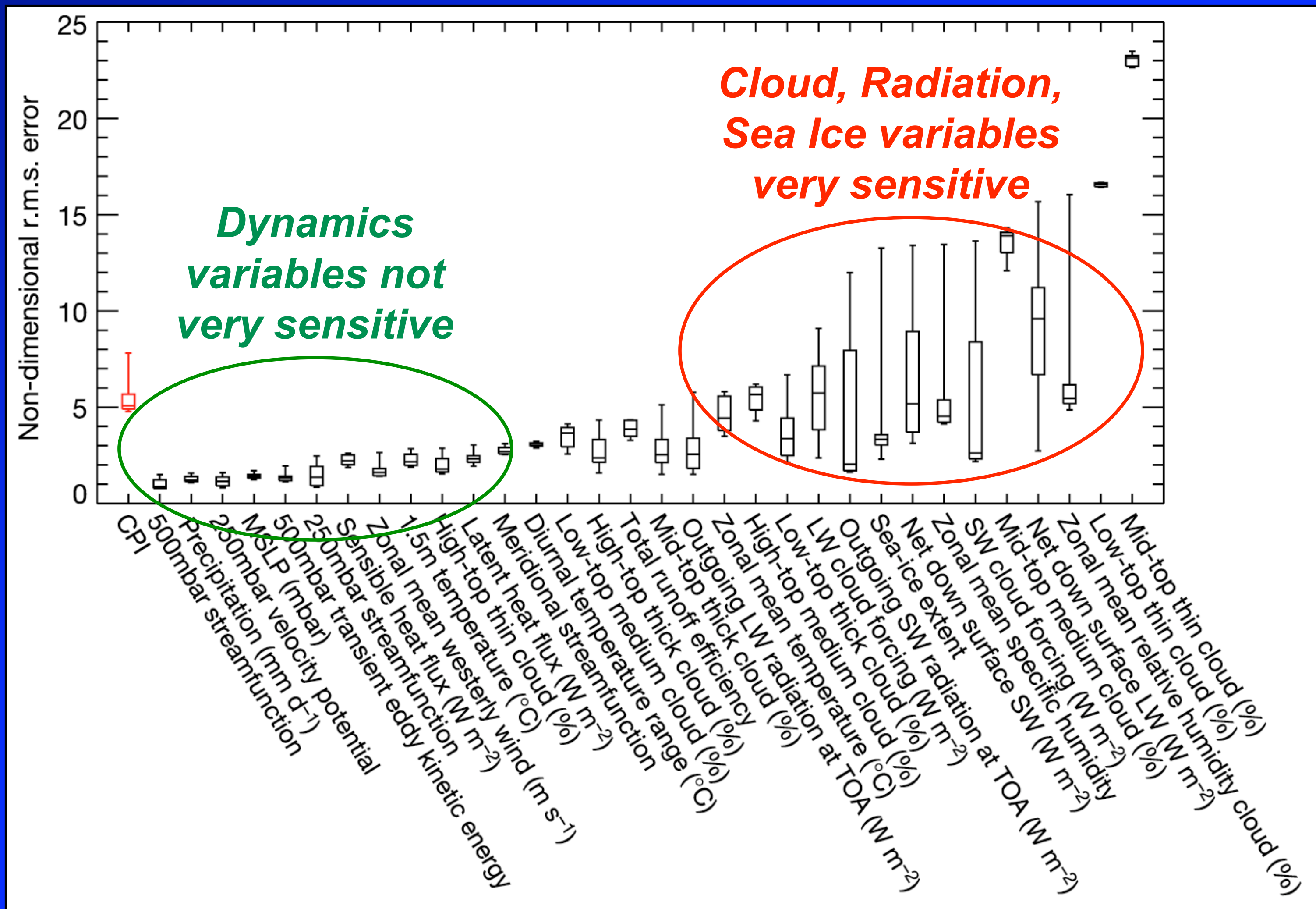
Anomalies in Relative Difference Between MODIS & CERES-Derived SW TOA Flux



Narrow-to-broadband errors in the MODIS-based approach introduces appreciable uncertainties in SW TOA flux changes that depend upon surface type (e.g., ocean vs land).

Loeb et al. 2007 J. Climate

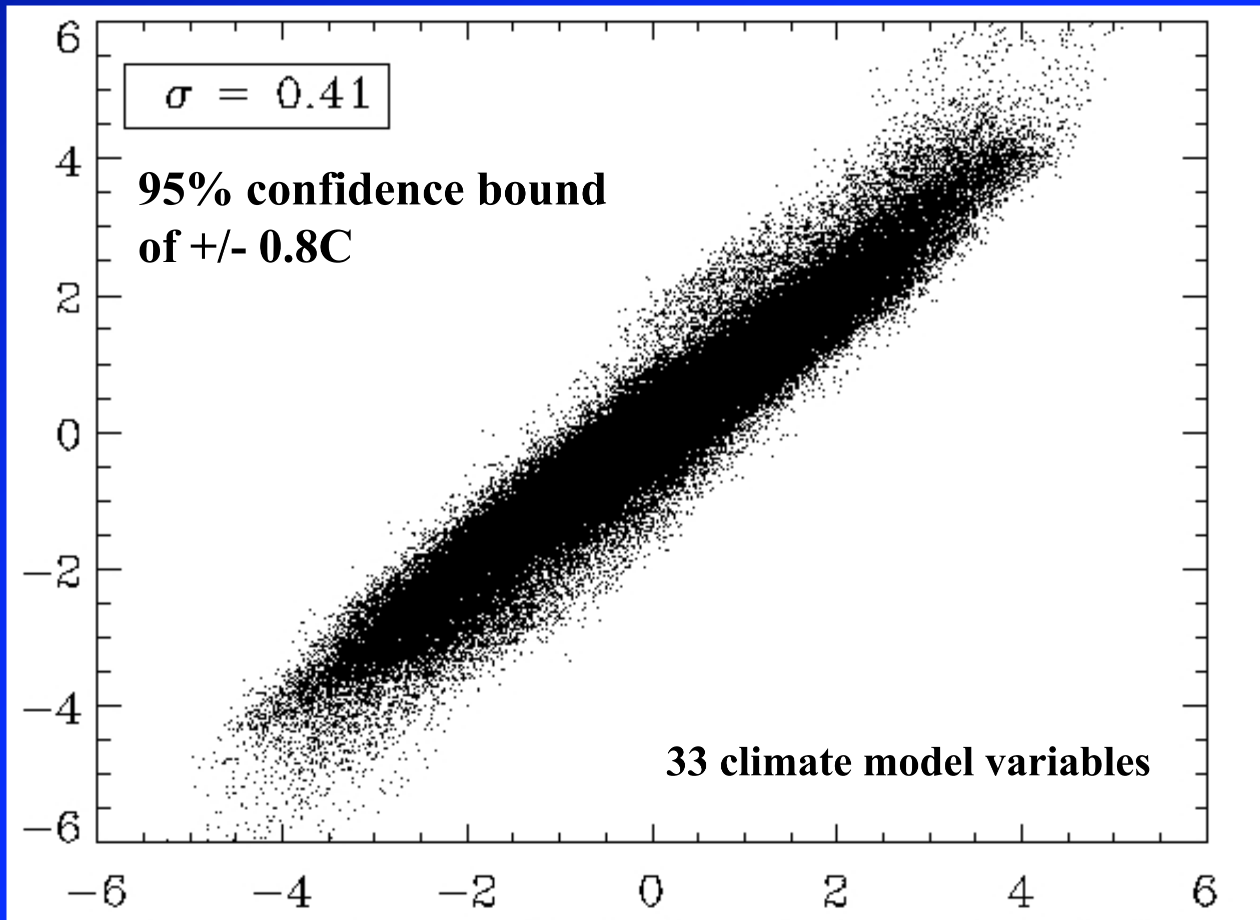
Amount of change for a factor of 6 in climate model sensitivity (2K to 12K for doubling CO_2)



Weather = dynamics, Climate = energetics
Need Climate Change OSSEs, Climate Obs. Reqmts

Murphy et al. Nature, 2004

Neural Net Prediction of Climate Sensitivity



Planet "I" minus Planet "J"
Doubled CO_2 Global Temp Change

Neural Net Prediction: Doubled CO_2 Global Temp Change
(uses Planet I and J normal CO_2 climate only)

Y. Hu, B. Wielicki, M. Allen

How Close in Viewing Angle to Calibrate?